ASSESSING THE POTENTIAL OF DISINFECTION BYPRODUCTS IN DRINKING WATER FROM GROUNDWATER IN NORTH CAROLINA AQUIFERS

By

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Executive Summary

Over half of the global population lives within 200 kilometers of a coastline. Many communities rely heavily on groundwater from coastal aquifers, which have distinct geochemical compositions based on geologic history, hydrogeology, and geographic positioning. Due to the proximity of these aquifers to seawater, they may have increased concentrations of halide ions including chloride, bromide, and iodide. Halides are important to quantify in drinking water because of their role in the formation of byproducts during drinking water disinfection.

In the United States, approximately 80% of drinking water is disinfected with chlorine. Halide ions have been relatively recently discovered to be precursors of disinfection byproducts (DBPs), some of which are classified as possible human carcinogens. The US Environmental Protection Agency (EPA) regulates four trihalomethanes (listed as Total Trihalomethanes or TTHM), with the main focus on chloride-induced DBP formation. However, recent studies have shown that bromide and iodide, although typically found in significantly lower concentrations, have the chemical potential to produce a higher amount of more toxic DBPs than those currently being regulated. Dissolved organic carbon (DOC) is another precursor, and although not well researched due to its unpredictable and variable structure, has still been proven to produce dangerous DBPs as well. Chloride is the only halide regulated by the EPA with a Maximum Contaminant Level (MCL) of 250 mg/L. Even though most public utilities meet this standard, many still see an elevated TTHM concentration, meaning other factors may be influencing DBP formation.

Our research goal was to quantify the geochemistry of various aquifers near the coast of North Carolina and to establish a correlation of an expanded number of halide concentrations, DOC concentrations, and DBP formation. We collected samples from wells in variable aquifers from nine public utilities along the coast, with each utility serving a relatively large population, using chlorination for disinfection, and reporting elevated TTHMs. We analyzed these for halide ion concentrations and DOC concentrations. Samples were also sent to Stanford University, where a lab ran a simulation analysis to quantify amounts of a range of regulated and unregulated DBPs that formed when the raw groundwater samples were chlorinated.

Our findings show that the ratio of chloride and bromide concentrations found in our samples resembles that of groundwater experiencing seawater intrusion. The formation of DBPs quantified in our analysis is significantly correlated with levels of bromide, iodide, DOC, and

electrical conductivity. Additionally, use of chloramines to disinfect the water resulted in significant reductions in TTHMs, and one of the major factors in formation, bromide, can also be significantly reduced with the usage of ion filtration systems such as reverse osmosis. These two methods could be potential options to reduce DBPs, by removing the constituents which contribute to their formation. Given the statistically significant correlation between TTHMs formed from drinking water disinfection and the levels of DOC and conductivity, we postulate that this could be a relatively inexpensive method of characterizing potential DBP formation in water prior to treatment, and could lead to the implementation of advance measures to reduce amounts of these compounds entering drinking water treatment systems.

Stresses such as over pumping, sea level rise, and seawater intrusion are viable threats to altering the geochemistry of coastal aquifers, with in increased risk of elevating these concentrations of halides. Identifying and understanding each factor and its role in DBP formation is necessary to monitor, prevent, and mitigate any changes to the drinking water supply as it relates to public health presently and in the future.

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Introduction

Over half of the world's population lives within 200 km of a coastline, and more than one billion people globally rely on coastal aquifers as a water source[1]. The population in U.S. coastline counties has grown steadily in recent years, with the Atlantic coastline region experiencing the largest gains since 1990[2]. In North Carolina, approximately 1.5 million people are supplied community water from coastal groundwater aquifers[3]. This research characterizes the chemical composition of groundwater between several aquifers in the North Carolina Coastal Plain and clarifies the factors that affect the relationship between geochemistry and disinfection byproduct (DBP) formation. By researching public drinking water utilities use groundwater, sampling source and treated water, characterizing the geochemistry of the aquifers, and simulating disinfection to quantify DBP formation, we can better identify the causes of elevated DBP occurrence throughout the North Carolina Coastal Plain and use these results as a tool for predicting DBP formation in coastal communities.

Coastal Plain

The Coastal Plain of North Carolina is part of the Atlantic and Gulf Coastal Plain physiographic province of the United States, which extends from Cape Cod, Massachusetts south and west into Texas. In North Carolina, the Coastal Plain is roughly 90-150 miles wide from the Atlantic Ocean west to the Fall Line. It is comprised of the eastern 41 counties and makes up about 45% of the state's total land area, as shown in Figure 1 below[4]. The Fall Line characterizes the boundary between the crystalline basement rocks of the Piedmont and the sedimentary rocks of the Coastal Plain. We chose the Coastal Plain as our research area because many communities within this region use groundwater as a primary drinking water source, and with close proximity to the ocean and the geologic history, salinity of drinking water is already a concern for utilities.

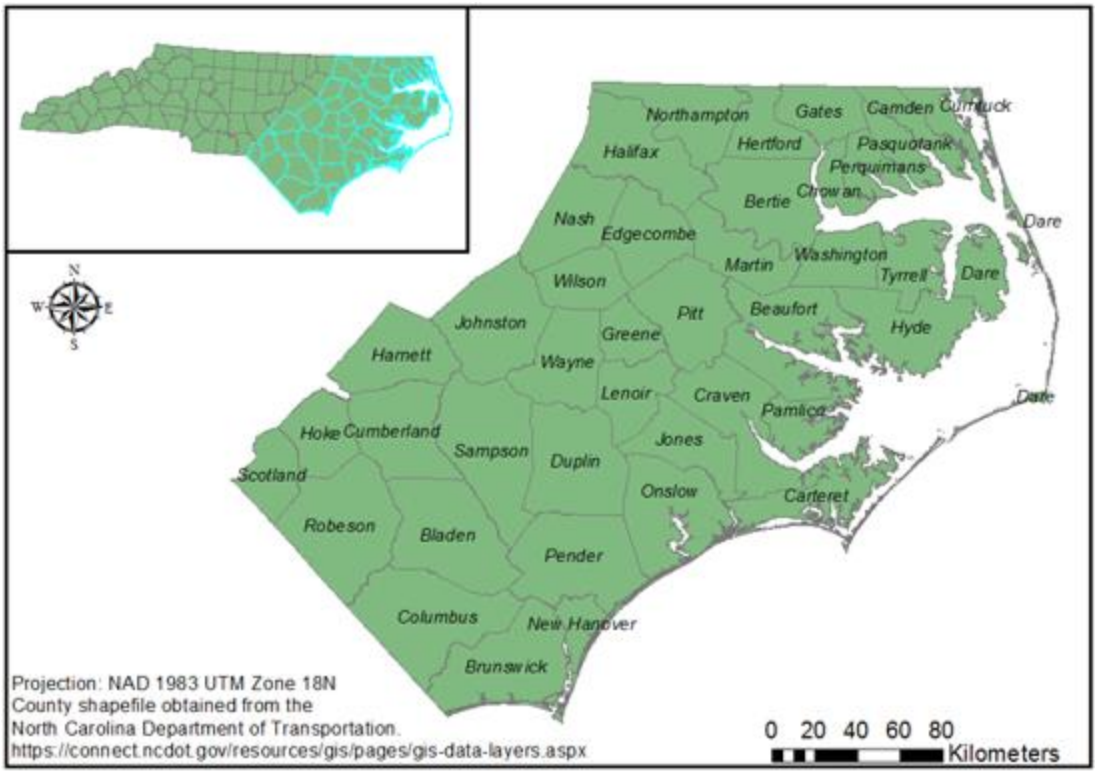

Figure 1: North Carolina Coastal Plain Counties.

Geology

The regional structure of sedimentary rocks of the Coastal Plain area is a broad eastward-dipping monocline, shown in Figure 2, which plunges southeastward[5]. Underlying the sediments of the Coastal Plain are crystalline Precambrian rocks of the Piedmont physiographic province. The Coastal Plain sediments were deposited under nonmarine and marginal marine conditions throughout the transgression and regression of the Atlantic Ocean[6]. Sediments dip and thicken eastward from the Fall Line, spanning from the Lower Cretaceous to the Quaternary in age[7]. Our focus encompasses the geologic units which comprise the selected aquifers of our study.

Hydrogeology

The North Carolina Coastal Plain aquifer system consists of ten aquifers separated by nine confining units. From top to bottom, the aquifers are the Surficial, Yorktown, Pungo River, Castle Hayne, Beaufort, Peedee, Black Creek, Upper Cape Fear, Lower Cape Fear, and Lower Cretaceous. The geologic formations and aquifers are contrasted in Figures 2A and 2B, below. In this study, we focus on the five most productive aquifers in the region: Yorktown, Castle Hayne, Peedee, Black Creek, and Upper Cape Fear.

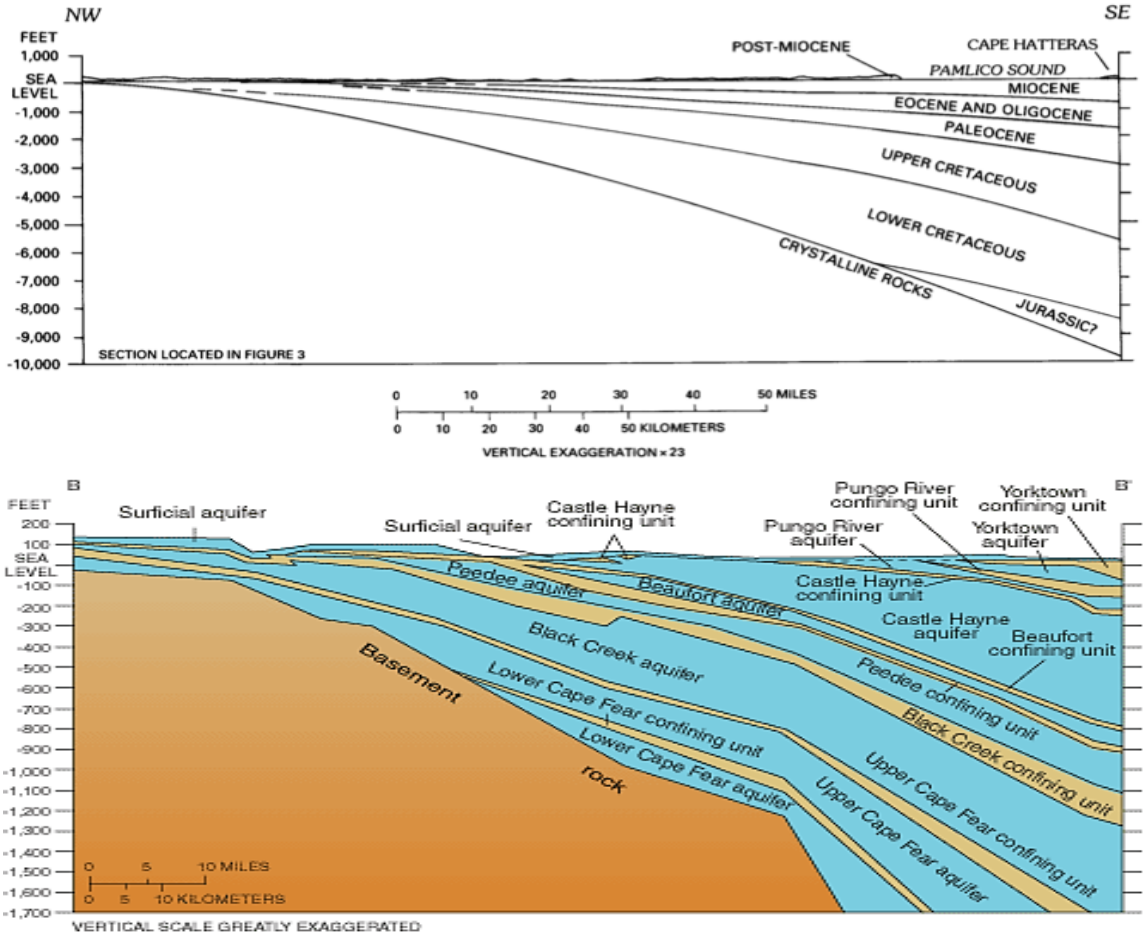

Figure 2: Figure 2A represents the geologic units of the Coastal Plain of North Carolina[2]. Figure 2B represents the groundwater aquifers of the Coastal Plain[8].

Beginning with the oldest formation, The Lower Cape Fear aquifer is composed of older sand beds of the Cape Fear formation[6]. In this formation, our main focus is the Upper Cape Fear aquifer, which comprises the permeable zones in the Cape Fear formation and is the lowest member in the Peedee-Upper Cape Fear aquifer system. The Upper Cape Fear consists of alternating beds of fine-to-medium grained quartz sand and clay that are commonly 3-5 feet thick but can attain a thickness of fraction of a foot to over 15 feet[7].

The Black Creek aquifer consists mainly of sediments of both Black Creek and Middendorf formations of the Late Cretaceous age[6]. The Black Creek formation was deposited in lagoonal and marine environments, and consists of thinly laminated gray to black clay interlayered with gray-to-tan lignitic, glauconitic, and shelly sands[10]. The Middendorf formation is composed of a heterogeneous mix of fine- to medium- grained sand and silty clay beds, coarse channel sand, and thin laminated beds of sand and clay, all of nonmarine origin. Beds can be white, tan, and red in color, and often contains kaolinite fragments[6]. The Black Creek aquifer is the thickest and most productive in the Peedee-Upper Cape Fear aquifer system[7].

The Peedee aquifer is comprised largely of the Late Cretaceous age Peedee formation and is contains of fine- to medium- grained quartz sand interbedded with gray-to-black marine clay and silt[7]. Sand beds are commonly gray or greenish-gray and contain varying amounts of glauconite and shell material[10]. It is the youngest member of the Peedee-Upper Cape Fear aquifer system.

The Castle Hayne aquifer includes sediment from the Pungo River Miocene, the upper part of the Paleocene Beaufort formation[9], and the Eocene Castle Hayne limestone with rocks overlying of Oligocene-age clay. The units were deposited under marine conditions, and are composed predominantly of limestone and sandy marl[10], with trace amounts of clay. Shells, limestone, and sandy limestones, in addition to the sand beds are variable in their carbonate content. Geophysical logs show increasing silt and clay content near the bottom of the aquifer. Along its western margin from New Hanover County to Craven County, the Castle Hayne can be found near land surface and exposed in many streams, but it does not extend to the western or southwestern margins of the Coastal Plain[7]. As it dips eastward, the aquifer thickens considerably, to more than 950 feet thick in Carteret County[6]. Due to this high volume, the Castle Hayne is the most productive aquifer in North Carolina, with over 65 million gallons being pumped daily for industry alone[6].

The Yorktown aquifer is generally equated with the Pliocene Yorktown and the upper Miocene Eastover formations. It extends throughout the northern half of the North Carolina Coastal Plain from the Fall Line eastward to and beyond the coast. The aquifer thickens eastward, and although not present in most of the southern half of the Coastal Plain, attains a thickness of more than 300 feet in Dare County[6]. It is composed largely of fine sand, silty and clayey sand, and clay and carbonate shell material, with sediments deposited in marine and near-marine environments[6].

Evaluating the geology and hydrogeology of our research area is essential to the understanding of the origin and presence of potential geochemical constituents in the groundwater. By using this information in concert with disinfection chemistry, we can better explain DBP formation potential in groundwater throughout the region.

Disinfection Chemistry and Byproduct Formation

Disinfection of drinking water occurs when utilities add chlorine (or a similar oxidant) to source water in order to inactivate pathogens for potable use. This process has played a critical role in improving drinking water quality in the United States since its first application in 1908. Soon after, most of the U.S. began routine disinfection of community drinking water[11]. Increase in disinfection contributed a dramatic decrease in waterborne disease across the country, particularly cholera, typhoid and dysentery. The successful implementation of disinfection methods for public drinking water is considered one of the greatest public health achievements of the 20th century[11].

Two primary methods to control biological growth and remove color, taste, and odor compounds in the U.S. are chlorination and chloramination. 80% of utilities nationwide disinfect via chlorination, which is the process of adding chlorine, a strong oxidant[12]. Chlorine is available as compressed elemental gas, sodium hypochlorite solution (NaOCl) or solid calcium hypochlorite ($Ca(OCl)_2$)[12]. The remaining 20% of utilities disinfect via chloramination, which uses a group of compounds containing chlorine and ammonia to disinfect water. Monochloramine (NH_2Cl) is typically used in this method[13].

Currently, chlorination is a more popular disinfection method than chloramination for several reasons. Chlorine has a longer residual time in water distribution systems, which increases the probability of pathogen inactivation throughout the distribution system[12]. In

addition to being more effective, it is also less costly, and treatment can occur at a higher pH which does not result in internal pipe corrosion[12]. Chlorination can lead to higher trihalomethane formation whereas chloramination typically produces higher concentrations of another group of DBPs, haloacetic acids (HAAs)[14].

In the 1970's, chloroform and other trihalomethanes were discovered as byproducts of chlorinating drinking water. Initially, industrial contaminants or chlorine impurities were believed to be the cause, but it was eventually determined that trihalomethanes were forming from dissolved natural organic matter and added chlorine. Chloroform is almost always the predominant constituent of trihalomethanes and is responsible for over 50% of the concentrations in chlorinated drinking water, however bromoforms and iodoforms are also detected in quantifiable concentrations[14].

Trihalomethane production from organic matter (mechanism (3) in electrophilic substitution listed above) in water proceeds via a series of reaction involving enolizable compounds, which are substrates for haloform reactions[14]. The reaction begins, as shown in Figure 3, with electrophilic addition of a halide species to the α carbon of an enolized carbonyl molecule. Initial electrophilic addition leads to increased addition of chlorine atoms, and ultimately hydrolysis yields a THM and a carboxylic acid[14]. Because the first step occurs in the presence of a base and the final step is a base hydrolysis, the reaction rate increases in basic conditions.

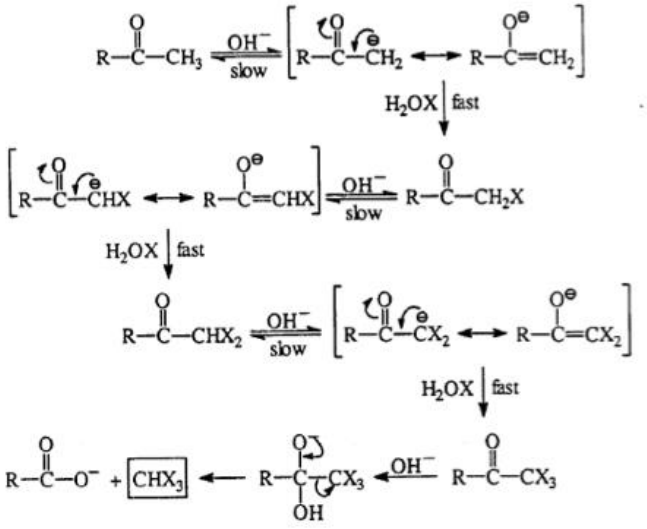

Figure 3: Mechanism of Haloform Reaction[14].

The main sources of other haloform compounds including bromoform and iodoform in drinking water are halide ions. Bromide ions are rapidly oxidized by HOCl to form hypobromite (HOBr), which is a more effective halogenating agent than hypochlorite, but a weaker oxidant[14]. Even at lower concentrations, it can outcompete HOCl as a source for organic halogens. In coastal areas, this can be especially concerning as bromide is considered a major ion in both seawater and evaporite deposits[14].

Natural organic matter (NOM) is also an important precursor of trihalomethanes in drinking water. Humic acids have a complex environmental chemistry with respect to reactions with chlorine disinfectants[14]. Chlorination of humic acids results in the incorporation of approximately 2% of the total chlorine. Many of these products are halogenated methanes and acids. Chlorination of heavier organic molecules increases the percentage of total chlorine in the NOM fraction. Mechanistic understanding of the pathways by which may of the humic-derived DBPs are formed is still unclear.

Disinfection Regulation

The Environmental Protection Agency's (EPA) National Primary Drinking Water Regulations are legally enforceable standards for public water systems that include four DBPs/classes of DBPs: bromate, chlorite, haloacetic acids (HAA5), and total trihalomethanes (TTHMs). TTHMs, are a group of DBPs consisting of four trihalomethanes[13]:

- Chloroform ($CHCl_{3)}$
- Bromodichloromethane ($CHCl_2Br$)
- Dibromochloromethane ($CHClBr_2$)
- Bromoform ($CHBr_3$)[13]

Of these, the International Agency for Research on Cancer (IARC) classifies both chloroform and bromodichloromethane as possible human carcinogens; dibromodichloromethane and bromoform have not conclusively been correlated to human carcinogenicity[16]. The EPA Maximum Contaminant Level (MCL) for TTHMs is 80 ppm, meaning the sum of the concentrations for each of the four regulated trihalomethanes must not exceed 0.080 mg/L[13].

These four compounds are not the only trihalomethanes that can form as a result of chlorination. More than 500 halogenated DBPs have been identified, and that list is likely to

grow. Recent studies have demonstrated that many nonregulated DBPs are more cytotoxic and genotoxic than the currently regulated THMs and HAAs[15]. One study concluded that N-containing DBPs are more toxic than halogenated carbonaceous DBPs and that iodine- and bromine- containing DBPs are more toxic than their chlorinated analogues[17].

Studies which disinfect water samples containing various levels of bromide and iodide have shown that trihalomethane concentrations increase with increasing bromide concentrations, with iodide concentrations leading to the formation of the highest levels of trihalomethanes[18]. The maximum concentration was found with iodide concentrations of approximately 2 micromoles/liter, and trihalomethane concentrations decreased when iodide levels increased past that threshold[18]. The study also remarks that Total Organic Carbon (TOC) and NOM affect the amount of byproducts formed in extremely complex reaction processes[19]. Because bromide and iodide can be found in elevated amounts in coastal aquifers that are in close proximity to seawater or that are at risk for salinization, this potentially poses a large public health risk to coastal communities that rely on disinfected groundwater for drinking.

Materials and Methods

Through a review of North Carolina Coastal Plain drinking water utilities, a dataset was generated of 43 water utilities relying on Coastal Plain aquifers in North Carolina. From this list, a total of nine public utilities were chosen for groundwater sample collection. This was accomplished through the use of a GIS model, shown in Figure 4 which was created to select utilities based on the following criteria:

- Population: In an attempt to quantify the largest effect on population of DBPs in drinking water, utilities that served a population greater than 1,000 were selected, which is shown in Figure 5 on the following page.
- Disinfection method: The primary DBPs focused on in this study are THMs, hence public utilities using only chlorination were kept for consideration. This also maintains an aspect of continuity across utilities and aquifers.

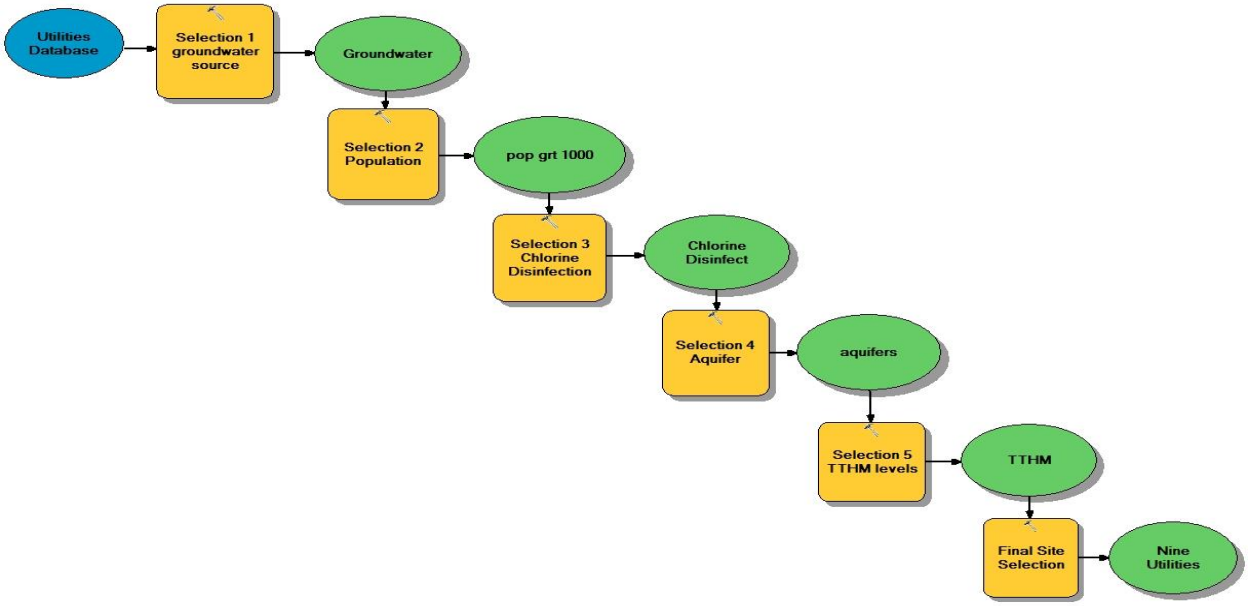

Figure 4: ArcGIS model developed to select of potential utilities to sample based on a set of pre-determined criteria.

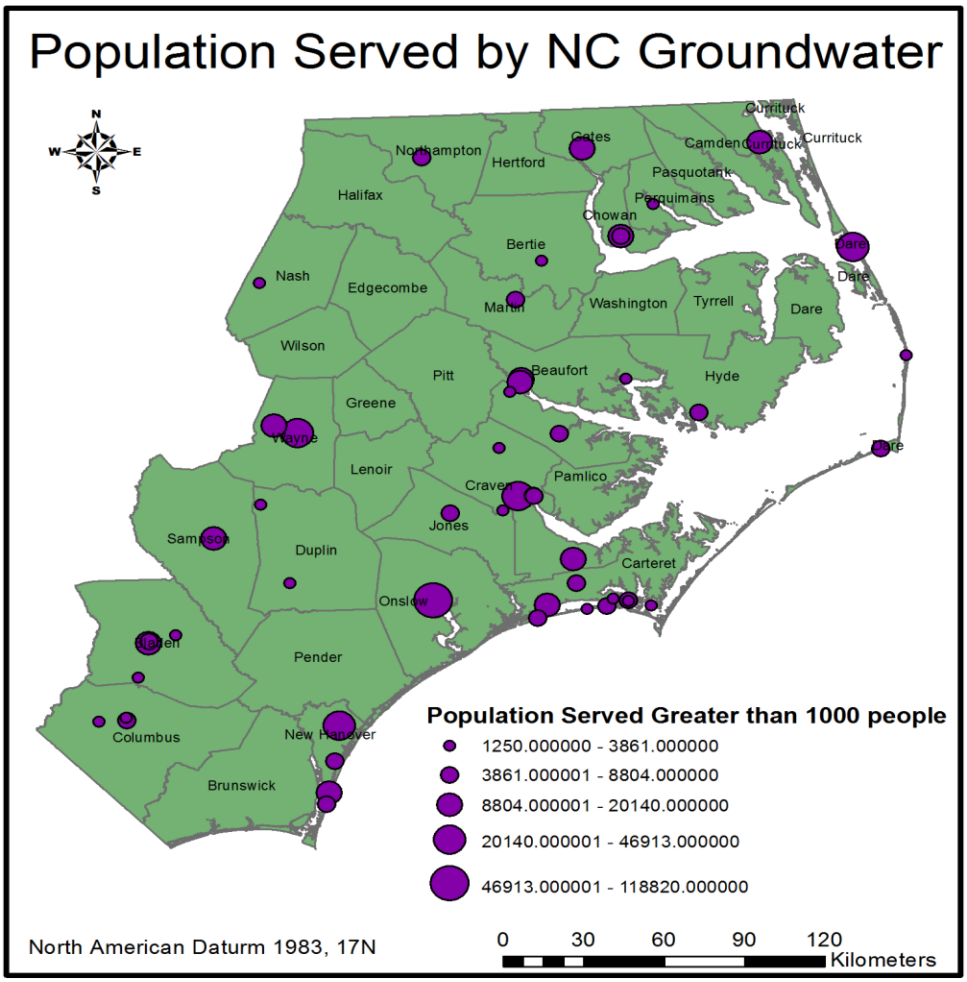

Figure 5: The populations served by the database of drinking water providers in Eastern North Carolina that use groundwater, developed for this research.

- Aquifer: A list of utilities was compiled to sample from the various aquifers utilized in NC that maintains an adequate representation of the total use of each aquifer throughout the Coastal Plain. The graph below displays all of the aquifers used by the 43 utilities within the Coastal Plain.

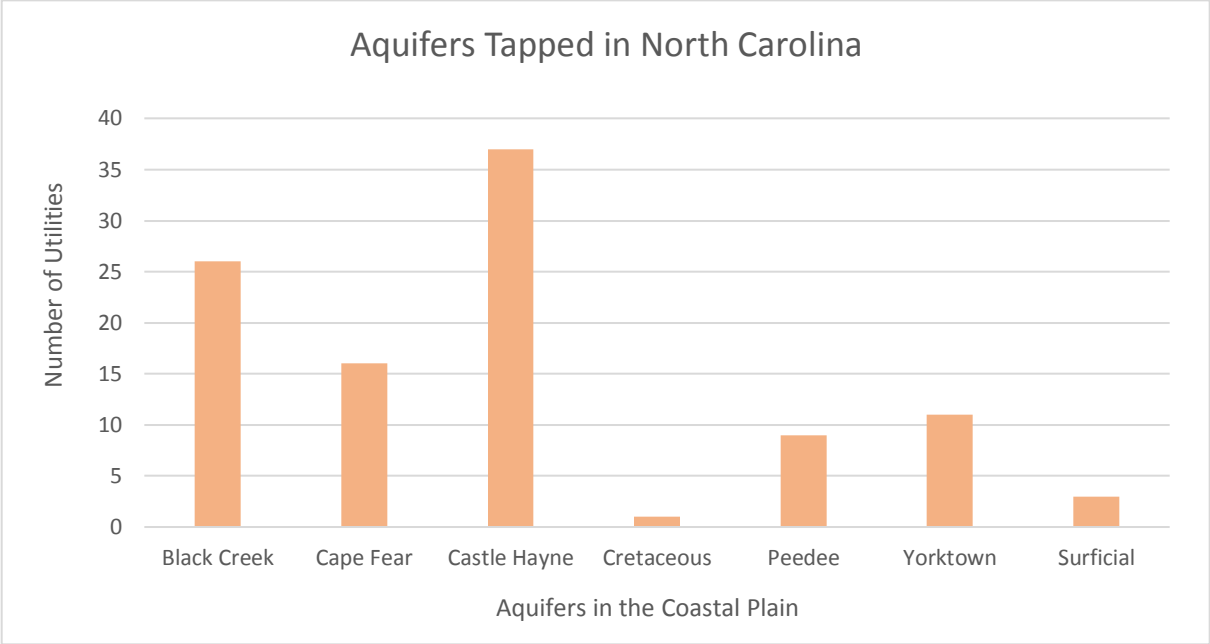

Figure 6: Graph of the usage of seven main aquifers by Eastern North Carolina Drinking Water Utilities. Based on the 43-utility database generated for this sampling collection and research.

- Trihalomethane concentrations: The Safe Drinking Water Act (1974) requires community water utilities to publish a Consumer Confidence Report (CCR) each year containing information regarding the water source and levels of detected contaminants. Trihalomethane concentrations from the most recent year available which were considered elevated (at approximately 30 ppb or higher) were the focus for this study. Total trihalomethane (TTHM) concentrations, recorded in utility water quality reports are provided in Figure 7 on the following page. The ArcGIS python script and further methodology are provided in Appendix E.

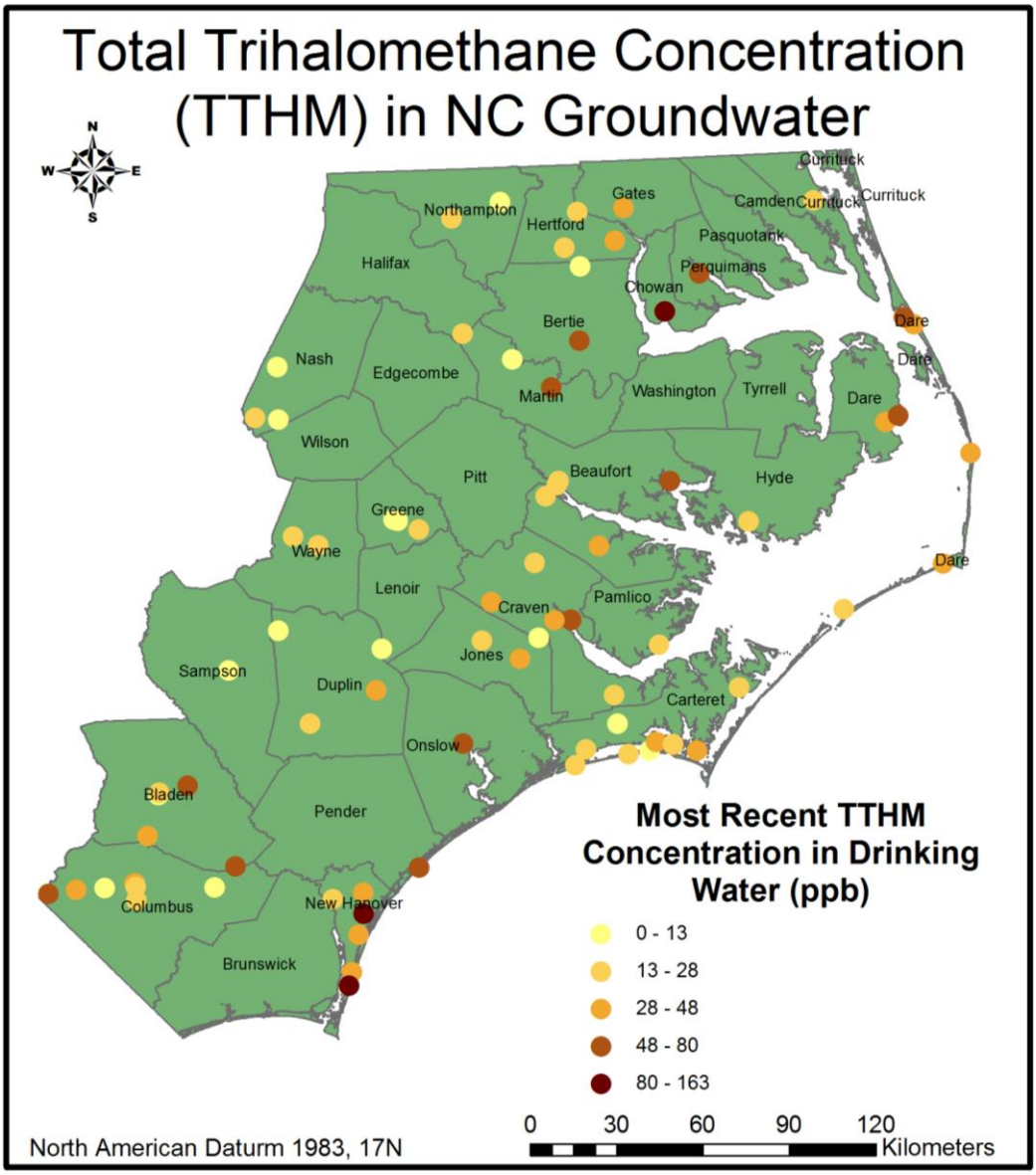

Figure 7: Map of most recently reported TTHM concentrations for 43 Groundwater utilities in Eastern North Carolina.

Two sampling trips were conducted in May and November of 2015 to six and three public water utilities, respectively. Information was collected from each utility on the depth of wells, pumping rates, and distribution. Using a Trimble GPS, data points were collected at the site of each well and monitoring sample and the data was brought back into ArcGIS through ArcPAD for geospatial analysis and spatial characterization of the geochemical results. Samples were collected from an average of 2-4 wells per utility using the Vengosh Lab sampling protocols. A sample of treated drinking water was collected along the distribution system as a

monitoring sample. Additionally, one to two bulk 1L grab samples of raw groundwater were collected from each well.

Samples were analyzed via a Dionex DX-2100 Ion Chromatography machine, a VG PlasmaQuad-3 Inductively Coupled Plasma Mass Spectrometer, and Direct Current Plasma Optical Emission Spectrometry. Additional tests were conducted measuring DOC, NH4, bicarbonate, and iodide. One of each bulk sample was used by the Mitch Lab at Stanford University for DBP simulation analysis. The following is an account of their methodology for conducting these analyses.

DBP Simulation Methodology

Prior to the addition of the oxidant, each sample was buffered at pH 8 using 4 mM borate buffer (unless otherwise noted). Free chlorine stocks were generated and standardized as described previously[21]. Briefly, for experiments involving application of free chlorine (HOCl), a sodium hypochlorite stock was standardized daily by UV absorbance (ε292 nm = 362 M−1 cm−1). Samples were treated with a HOCl dose needed to achieve a 1 mg/L as Cl2 residual after 24 h at room temperature (20 °C), as determined in preliminary experiments. Samples were held in the dark at room temperature for 24 h (for chlorinated samples)[21]. The total chlorine residual after these holding times was measured using the DPD colorimetric method. The chlorine residual was then quenched by addition of 35 mg/L ascorbic acid, and the samples were extracted immediately for analysis as described below[21].

Halogenated DBPs (primarily THMs and HANs) were analyzed by solid phase extraction (SPE; Varian Bond Elut-PPL, 200 mg, 3 mL) of 40 mL samples spiked with 1,2-dibromopropane as an internal standard based on the method of Chinn et al.44 Briefly, the cartridges were conditioned with 10 mL of methanol[21]. After passing the sample through the SPE cartridge, the cartridge was eluted with 2 mL of methyl tert-butyl ether (MtBE). The MtBE extract was dried with sodium sulfate anhydrous and analyzed using gas chromatography−mass spectroscopy (Agilent 240 GC-MS system). Aliquots (3 μL) were injected in splitless mode (inlet temperature 90 °C). DBPs were separated using a J&W DB-1701 column (30 m × 0.250 mm × 1 μm)[21]. The oven temperature was held at 35 °C for 23 min, then raised to 139 °C at 4 °C/min, and finally raised to 274 °C at 27 °C/min, where it was held for 1 min[21].

No DBPs were detected in deionized water blanks chlorinated as described above. Bromate (BrO_3^-) was analyzed using a Dionex DX-500 Ion Chromatograph equipped with an IonPac AS11-HC column[21]. A sodium hydroxide (50 mM) eluent was applied at 5% for 25 min, ramped to 50% for 2 min, and then held at 50% for an additional 20 min. Bromate (retention time, RT = 18 min) was separable from chloride (RT = 21 min)[21].

Table 1: List of DBPs reported from the Disinfection Simulation, including which correspond to the TTHM value reported by utilities, as well as the halogen ions each contains.

DBP	TTHM	Chlorinated Haloform	Brominated Haloform	Iodinated Haloform
Trichloromethane	+	+		
Bromodichloromethane	+	+	+	
Dibromochloromethane	+	+	+	
Tribromomethane	+		+	
Bromochloroiodomethane		+	+	+
Dibromoiodomethane			+	+
Chlorodiiodomethane		+		+
Bromodiiodomethane			+	+

Results and Discussion

A total of 32 samples were collected from nine public utilities, including monitoring samples, for which data is provided in Appendix A. Samples were collected from the aforementioned aquifers from utilities ranging in population from 4,500 to 118,000. Included in Appendix B is the data from a previous study conducted by the Vengosh Lab on groundwater on Hatteras Island and Manteo, located on the Outer Banks of North Carolina. A dataset from a USGS study in Brunswick, Pender, and New Hanover counties of the Castle Hayne and Peedee aquifers is included in Appendix C. Datasets in Appendices B and C were used as supplementary data in the geochemical analyses and characterizations.

Geospatial Analysis

Following sample collection, the results of the geochemical analysis were plotted in maps of the Coastal Plain to examine for any spatial trends in the data. The chloride and bromide concentrations are shown separately in Figures 8 and 9, below. Chloride concentrations exhibited a wide range, from close to the detection level up to over 2,700 ppm, or mg/L. Samples collected from three utilities tapping four aquifers contained chloride levels above the EPA MCL for chloride of 250 ppm, those include the Yorktown, Black Creek, Cape Fear, and Peedee aquifers. The highest chloride samples collected from the Yorktown aquifer undergo Reverse Osmosis or Anion Exchange to treat the water prior to disinfection, therefore the concentrations measured in the source water samples are not indicative of water obtained by consumers in Dare County. However, the other two utilities do not use any pretreatment filtration to remove the chloride ions.

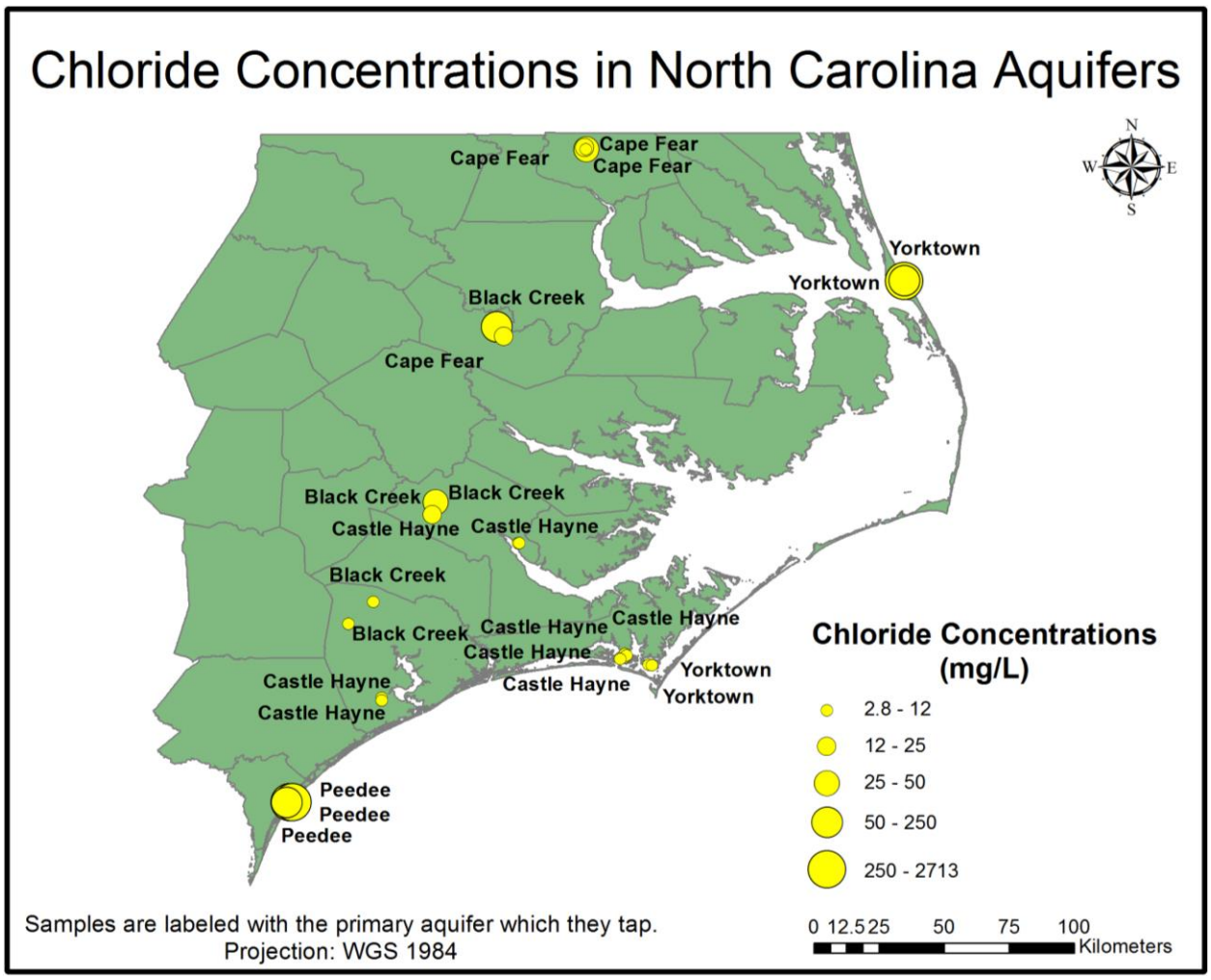

Figure 8: Spatial distribution of chloride ion concentrations in the collected raw groundwater samples.

Bromide concentrations in the water samples varied over a much smaller range, however a visible correlation to chloride concentrations can be observed. Again, the three largest sources of bromide were collected from the Yorktown, Cape Fear, Black Creek, and Peedee aquifers. There is, however no Maximum Contaminant Level for bromide in drinking water so this fact does not put any of these samples out of accordance with regulation, however previously discussed studies have shown that increased bromide concentrations do put communities at risk for generating higher levels of trihalomethanes.

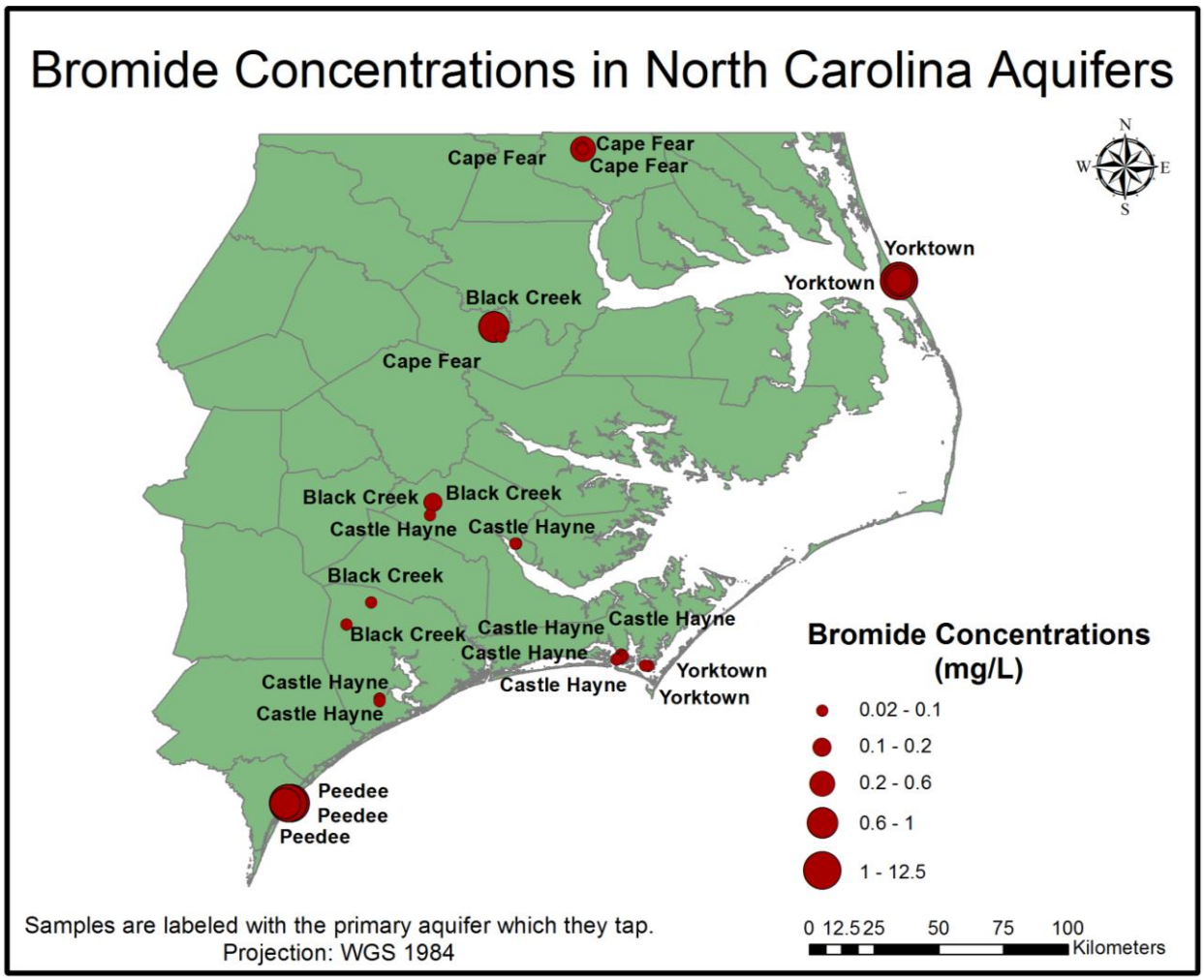

Figure 9: Spatial distribution of bromide ion concentrations in the collected raw groundwater samples.

The spatial variation in iodide concentrations in the water samples is shown in the figure below. The map demonstrates that there is less of a correlation between iodide (in ppb) with either bromide or chloride. The south-central coastal plain samples collected from the Black Creek and Castle Hayne aquifers contained some of the lowest concentrations of iodide. With the exception of the Northern Coastal Plain Cape Fear aquifer samples, the highest levels of iodide were reported to utilities along the coast, including some also collected from the Castle Hayne aquifer which reported lower levels of chloride and bromide compared to some of the other samples. The Northern Cape Fear samples may share more consistency with the Virginia portion of the aquifer system which can differ geochemically from the Southern samples, and could provide an explanation for this difference.

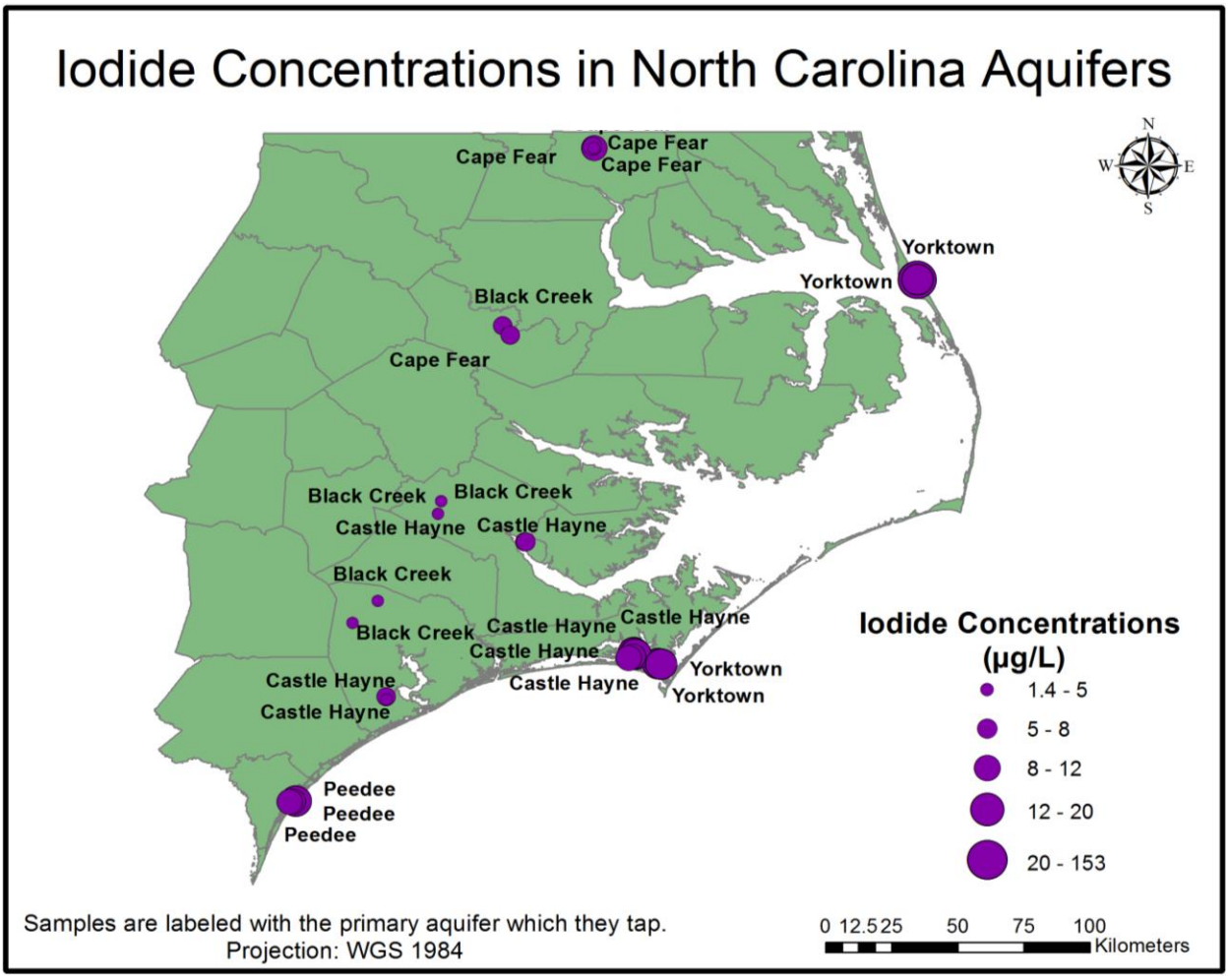

Figure 10: Spatial distribution of iodide concentrations in the collected raw groundwater samples.

Concentrations of dissolved organic carbon (DOC), a surrogate for organic matter in drinking water, were also plotted for the collected samples, and is shown in Figure 11. Here there appears to be a spatial trend with proximity to the coast which results in higher concentrations in drinking water, as demonstrated by the black arrows. Again, the samples collected from the Yorktown aquifer which exhibited the highest DOC levels at 79 are those which undergo Reverse Osmosis and the DOC concentrations present in the treated water are much lower. An analysis of the water post Reverse Osmosis revealed DOC concentrations of 0.256 mg/L, and all previous samples for the area contained more than 60 mg/L, suggesting this is an effective treatment for the removal of DOC in source water.

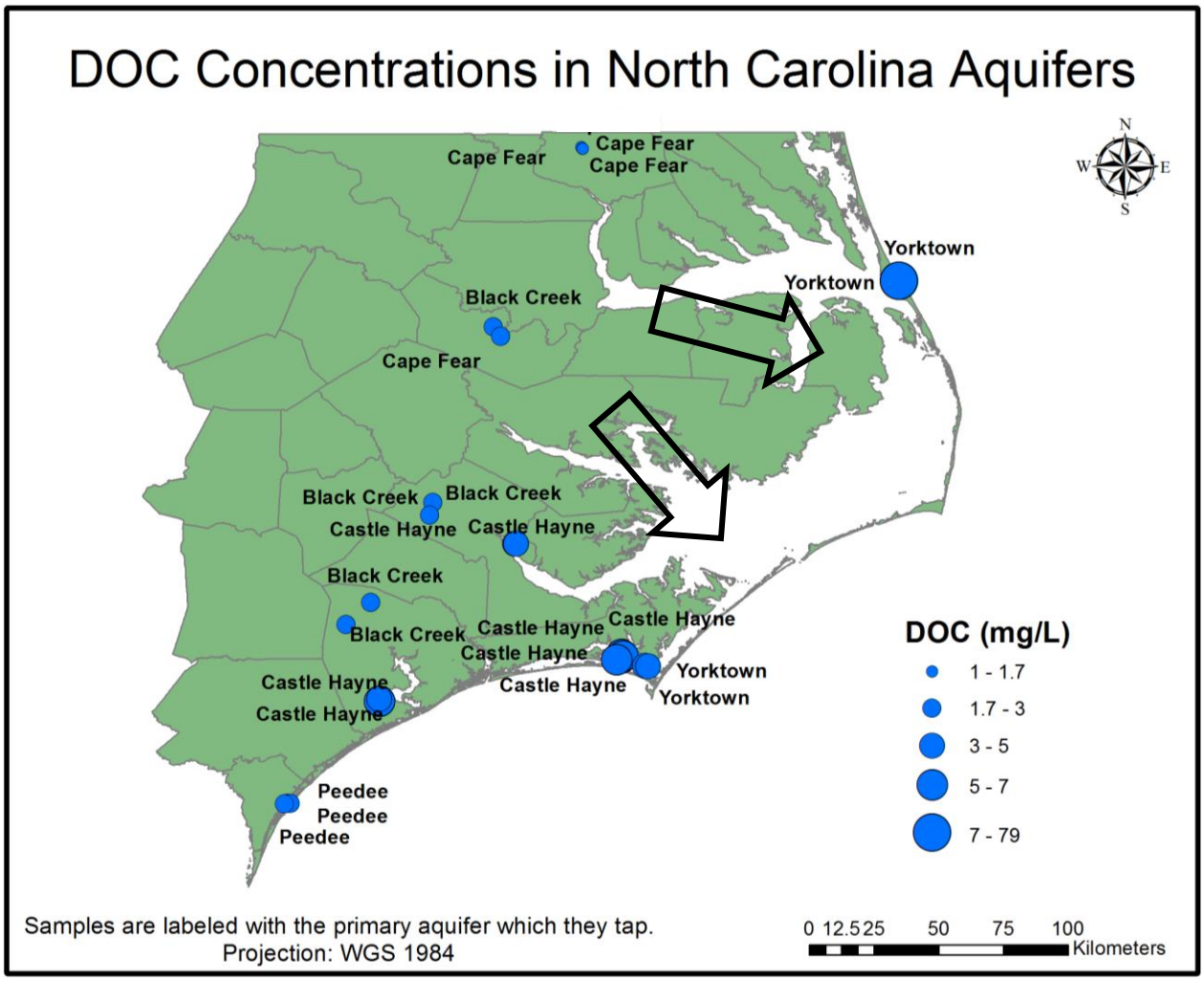

Figure 11: Spatial distribution of dissolved organic carbon concentrations in the collected raw groundwater samples.

Following this sample analysis bromide and chloride concentrations were also examined from several other studies to determine the continuity of these samples with previous research. What was also found was variability in chemical constituents between aquifers and within each aquifer. Figures 12 and 13 show the spatial variability among water samples from the Outer Banks of North Carolina. The southernmost samples are those treated via Reverse Osmosis prior to disinfection and contain high levels of bromide and chloride, up to approximately 25 and 8,000 mg/L, respectively. Even in a relatively small area, however, there is a wide range of concentrations, with no clear spatial trend relating the values. What can be seen from the images is that high chloride levels seem to correspond to high bromide levels across the Skyco samples, and the same appears true for the lower concentrations. These do not appear to be correlated with depth though. According to information provided by the utility, the highest chloride and bromide values, in wells 10, 11, 8, and 7 collectively span a screening depth of approximately 140-220 feet[22] which encompasses the range of screening depths for the other wells, including those with very low chloride levels.

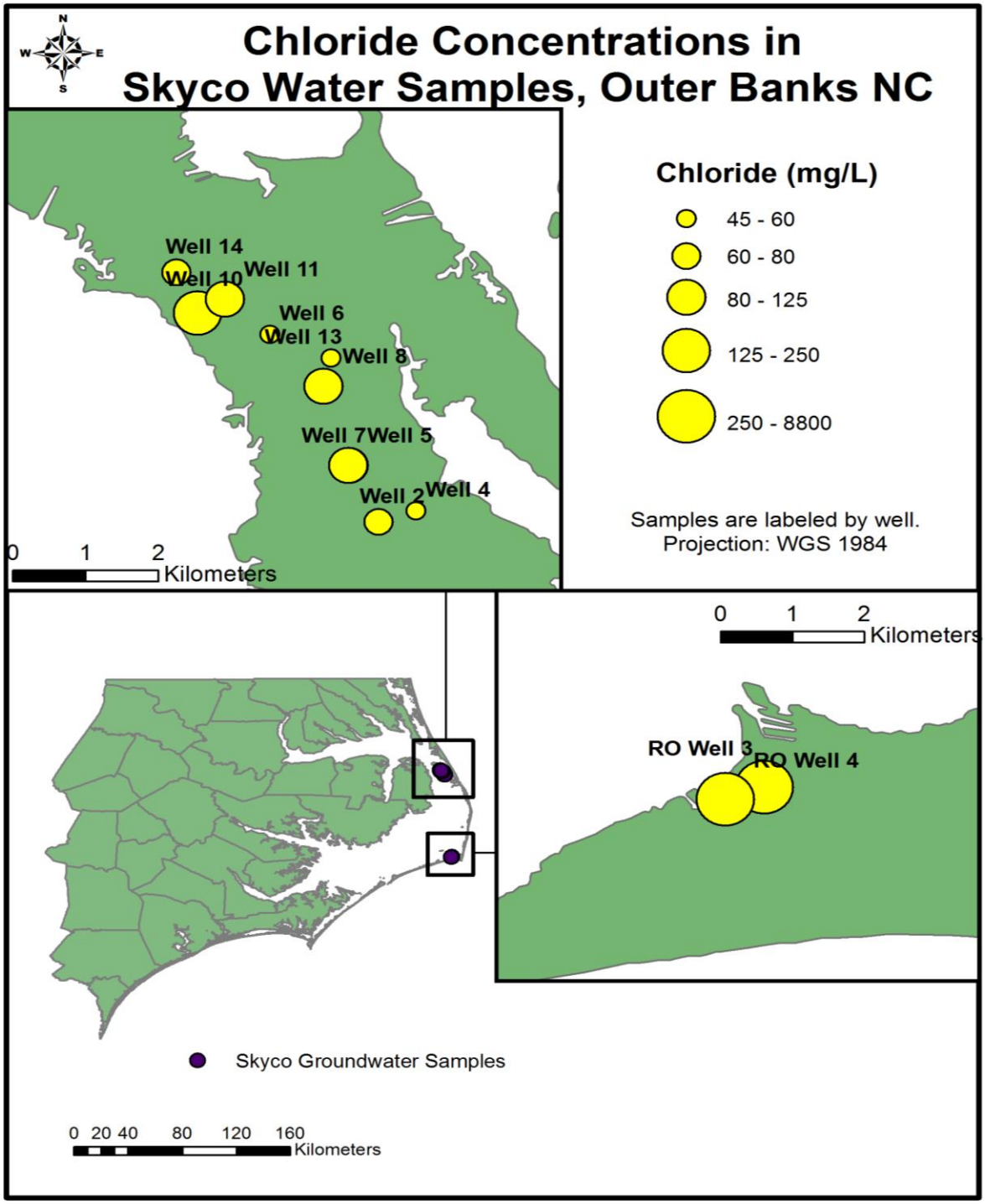

Figure 12: Spatial distribution of chloride ion concentrations in raw water samples collected from the Yorktown Aquifer in Dare County.

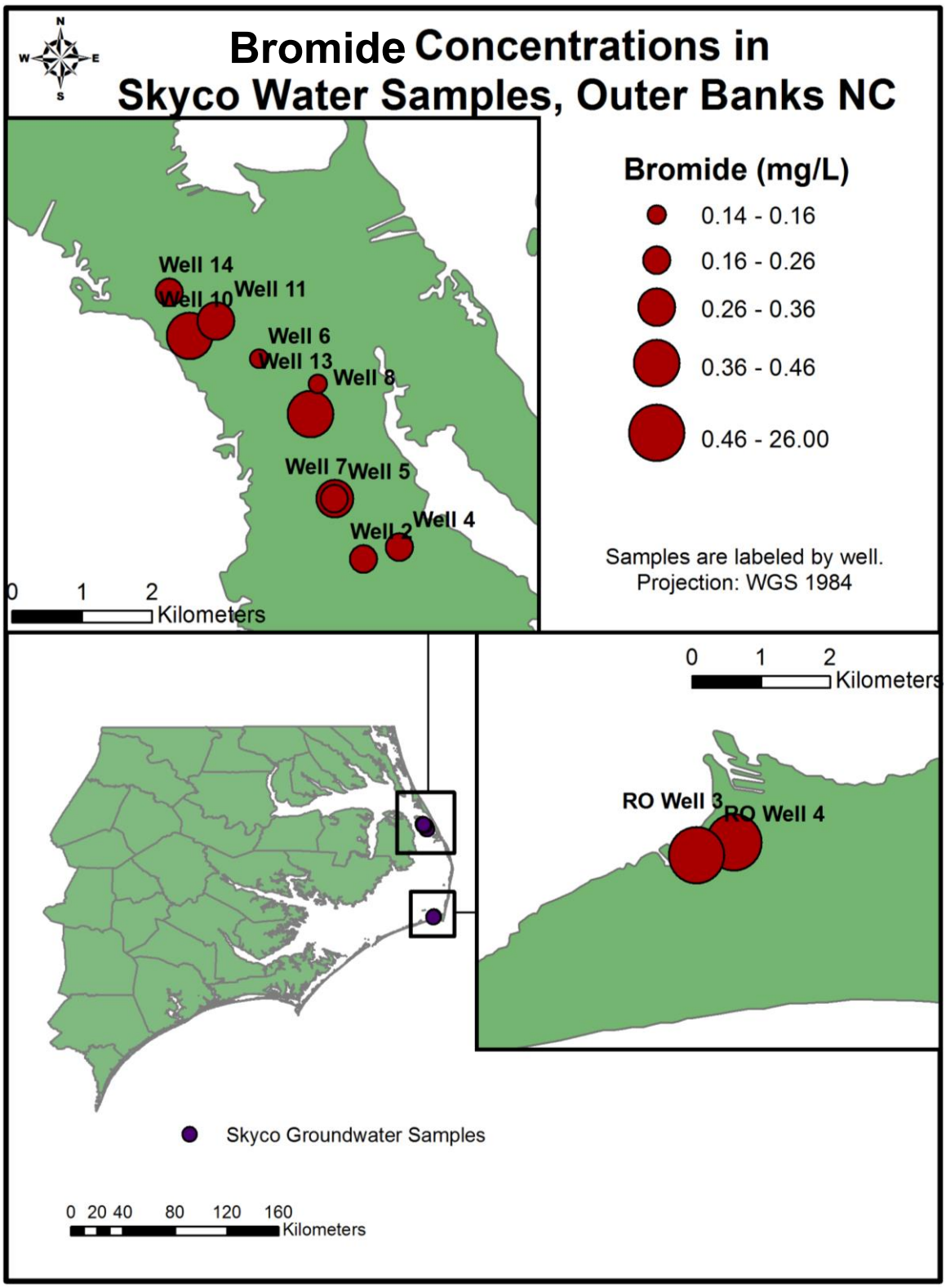

Figure 13: Spatial distribution of bromide ion concentrations in raw water samples collected from the Yorktown Aquifer in Dare County.

The sample data of the Castle Hayne and Peedee aquifers shows spatial variation within aquifers as well, and Figures 14 and 15 also show a correlation between bromide and chloride levels[23]. Samples collected from the Peedee aquifer did not show as high levels of chloride and bromide as did those collected from the Castle Hayne, although both exhibited fairly wide ranges. The majority of samples collected from New Hanover and Brunswick demonstrated low levels of chloride and bromide, up to 285 and 0.398 mg/L, respectively[23]. Two hot spots for high ion concentrations appear to be at the border between New Hanover and Pender, and at the southern point of Brunswick county, although scientists conducting the study had no explanation for the peak values at the time their report was published[23]. With this large variation, however, all collected source samples displayed in Figures 7 and 8 do exhibit bromide and chloride concentrations which are characteristic of previous samples for both of these aquifers.

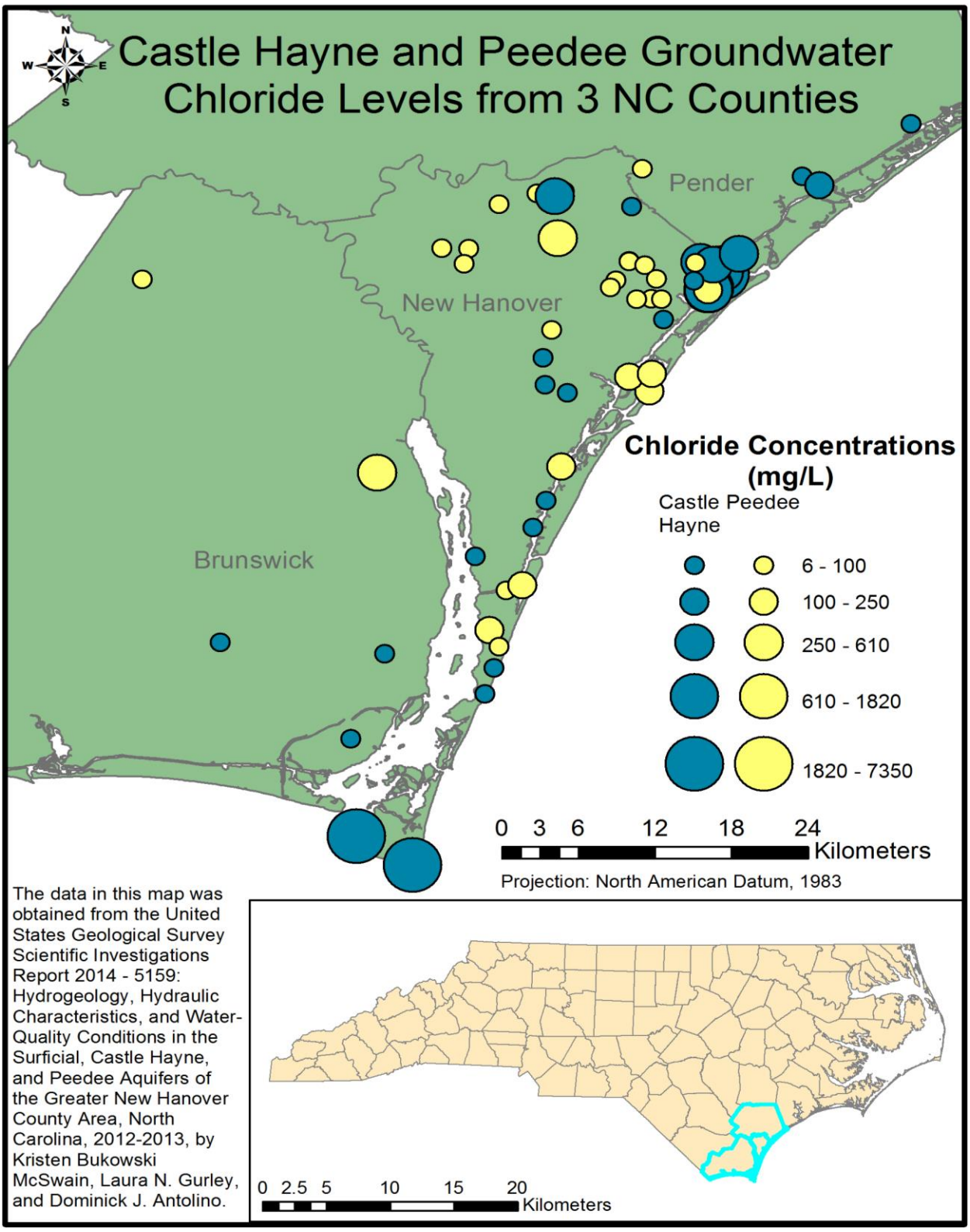

Figure 14: Spatial Distribution of Chloride ion concentrations in samples collected by the USGS for the Castle Hayne and Peedee Aquifers.[23]

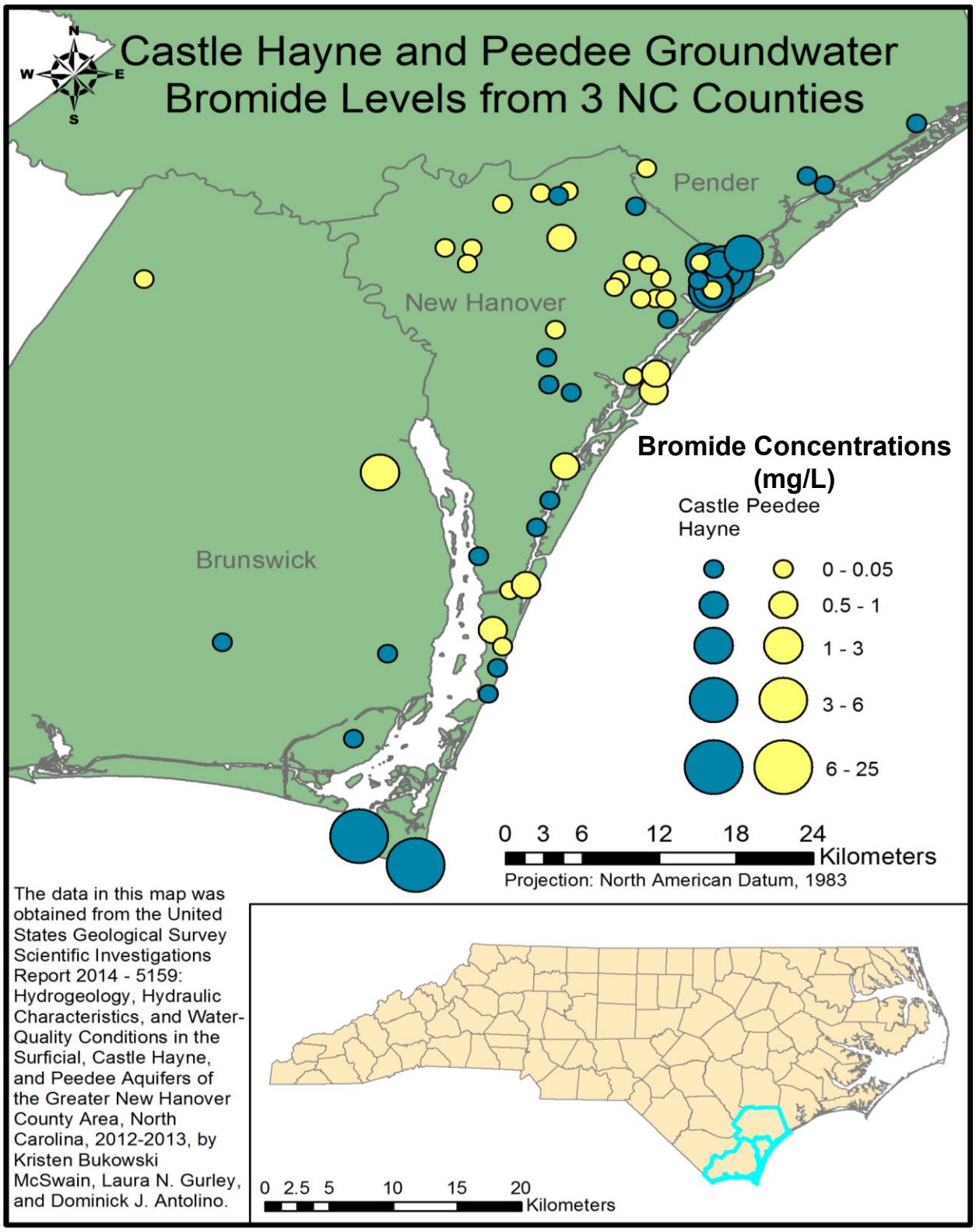

Figure 15: Spatial distribution of bromide ion concentrations from samples collected by the USGS in the Castle Hayne and Peedee Aquifers.[23]

The results of the disinfection simulation were mapped to examine the spatial variation in sample concentrations as well as compare results for individual aquifers. Samples shown in orange and red are those which contained totals of the four regulated trihalomethanes (TTHMs) which were above the EPA MCL of 80 ppb. This was the case for 15 out of the 25 simulated samples, and occurred largely for those collected from the Yorktown, Peedee, and Castle Hayne aquifers. In contrast, the lowest values were found in samples simulated from the Black Creek and Cape Fear aquifers. One Black Creek Sample was found to contain over 80 ppb of the four measured trihalomethanes, however it is important to note that samples are labeled with the primary aquifer tapped, and this well also pumps directly from the Peedee aquifer, where all disinfected samples generated greater than 80 ppb of these byproducts, hence that may have played a role in the findings for that sample. Interestingly, a sample from the Northern Coastal Plain collected from the Yorktown aquifer, specifically in Kill Devil Hills, that consistently had high chloride, bromide, iodide, and DOC levels, reported extremely low TTHM levels. A potential explanation is provided with the statistical analysis.

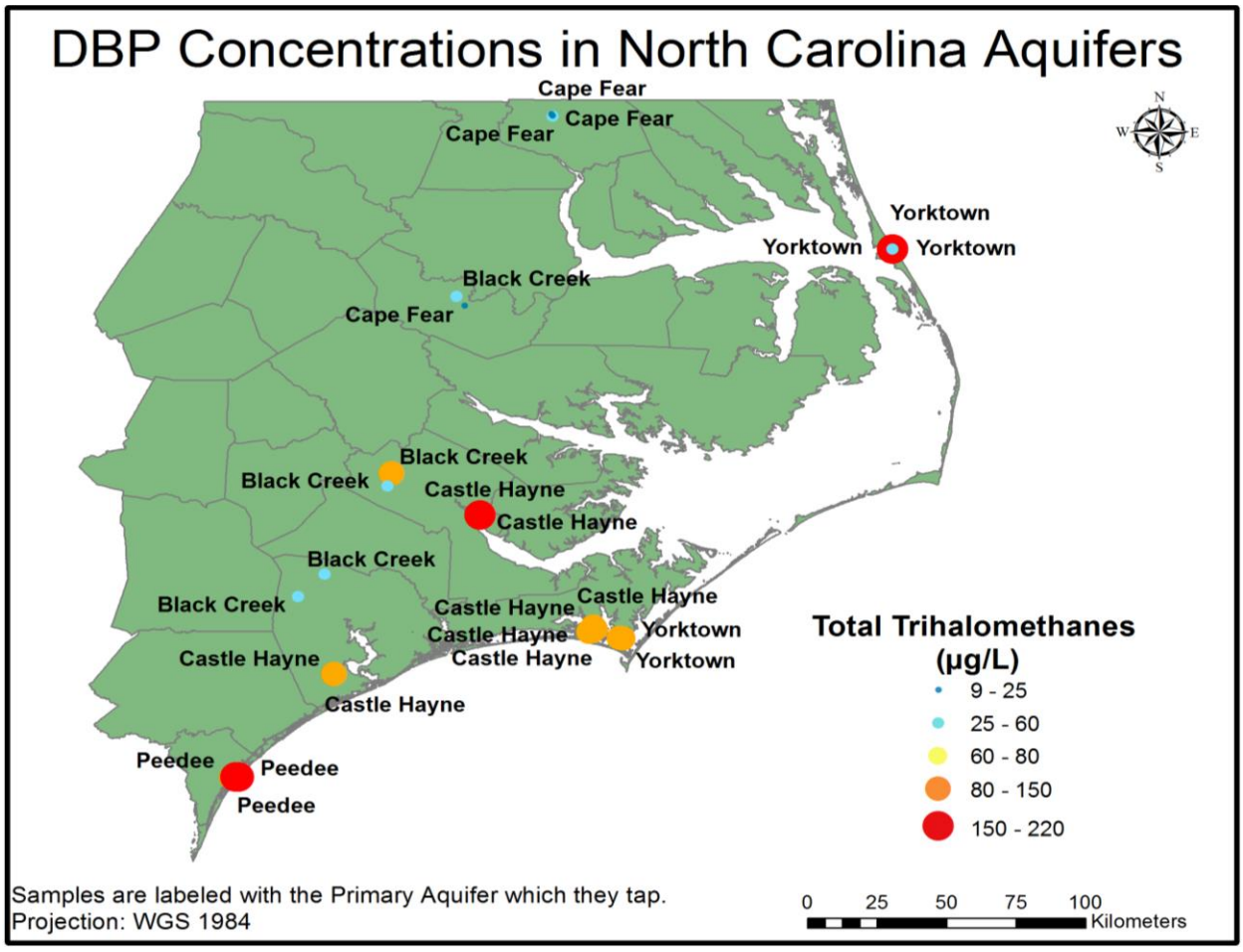

Figure 16: TTHM concentrations as results of disinfection simulation of raw groundwater samples.

Statistical Analysis

To characterize the geochemistry of the coastal aquifers, we began by examining the chloride to bromide (Cl/Br) ratios. Previous studies have used ratios of Cl/Br to detect the origin of salinity in groundwater as well as sources of anthropogenic contamination. The literature states that different Cl/Br ratios of groundwater are indicative of the following processes: (1) aquifers experiencing seawater intrusion will exhibit Cl/Br ratio of 293; (2) aquifers that originate from ancient evaporated seawater have a low (<300) Cl/Br ratio; and (3) groundwater that has dissolved evaporite minerals from surrounding geologic formations has a high (>300) Cl/Br ratio[24]. Figure 17a displays the bromide and chloride concentrations in each of the 32 collected samples plus supplementary OBX data. The data show a strong linear correlation (R^2=0.9468, P-value < 0.001, F-statistic$_{60\text{-}1}$=1086) between chloride and bromide concentrations of water samples collected. From our data, the average Cl/Br ratio is 300, which is well within error range of the seawater intrusion ratio. Cl/Br ratio trends excluding samples above the EPA MCL for chloride showed a similar trend, but with a slightly lower overall ratio of 264. This is very close to the seawater intrusion ratio and as the red line demonstrates in Figure 17b, which approximately follows the data clusters.

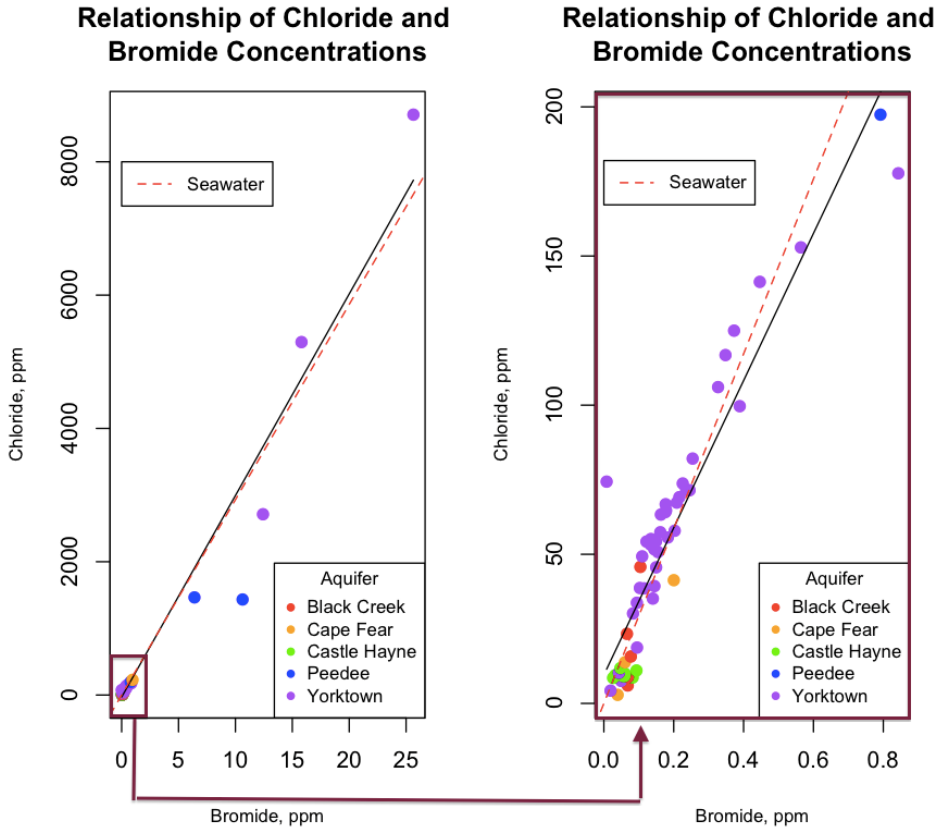

Figure 17: 17A displays bromide and chloride concentrations from all collected groundwater samples in this study. 17B shows the bottom left subsection, when removing the highest chloride values.

The first DBP precursor analyzed was chloride. According to the literature, chloride typically does not induce DBP formations unless the concentrations are very high, meaning we should not see a correlation. However, Figure 18a displays a significant correlation between chloride and TTHM concentrations (R^2=0.2472, P-value=0.0067, F-statistic$_{23\text{-}1}$=8.879). Two sample points with very high chloride concentrations well above the EPA MCL, both from the Wrightsville Beach Water System, may be skewing those results. These sample points also have high levels of DBPs, consistent with the literature. The red dashed line represents the EPA MCL threshold for TTHMs at 80 ppb (0.080 µg/L), and the green dashed line represents the EPA MCL for chloride of 250 mg/L. Even though most of our sample points have chloride concentrations below the MCL, most of those same points exceed the MCL for TTHMs. There is no correlation between chloride and chlorinated haloforms (R^2=0.04344, P-value=).9776, F-statistic$_{23}$-1=0.008), shown in Figure 18b. This is expected because chlorinated haloforms are a product of the chlorine used in disinfection.

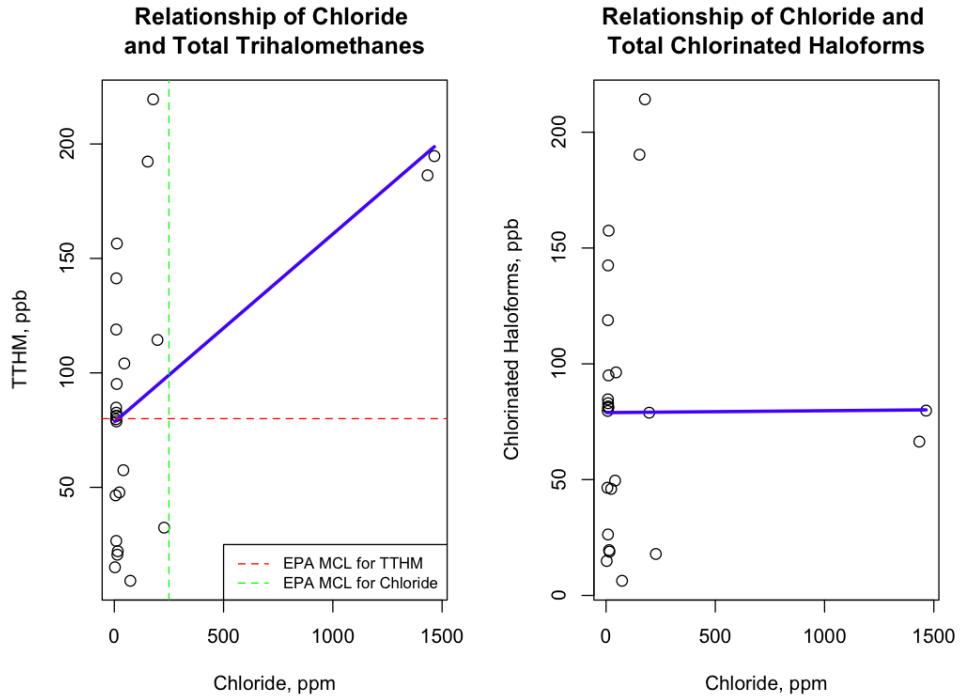

Figure 18: 18A: Relationship of Chloride to TTHM concentration. 18B: Relationship of Chloride to Chlorinated Haloforms.

Figure 18C displays the TTHM concentrations and chloride concentrations of samples where the chloride concentration was under the EPA MCL (250 ppm). Sample points are separated by color, which shows their respective dissolved organic carbon contents. An apparent

pattern should be noted in the figure, as DOC concentrations, regardless of chloride concentrations, seem to correlate with TTHM concentrations. The relationship between DOC and TTHM concentrations is further analyzed later in the discussion.

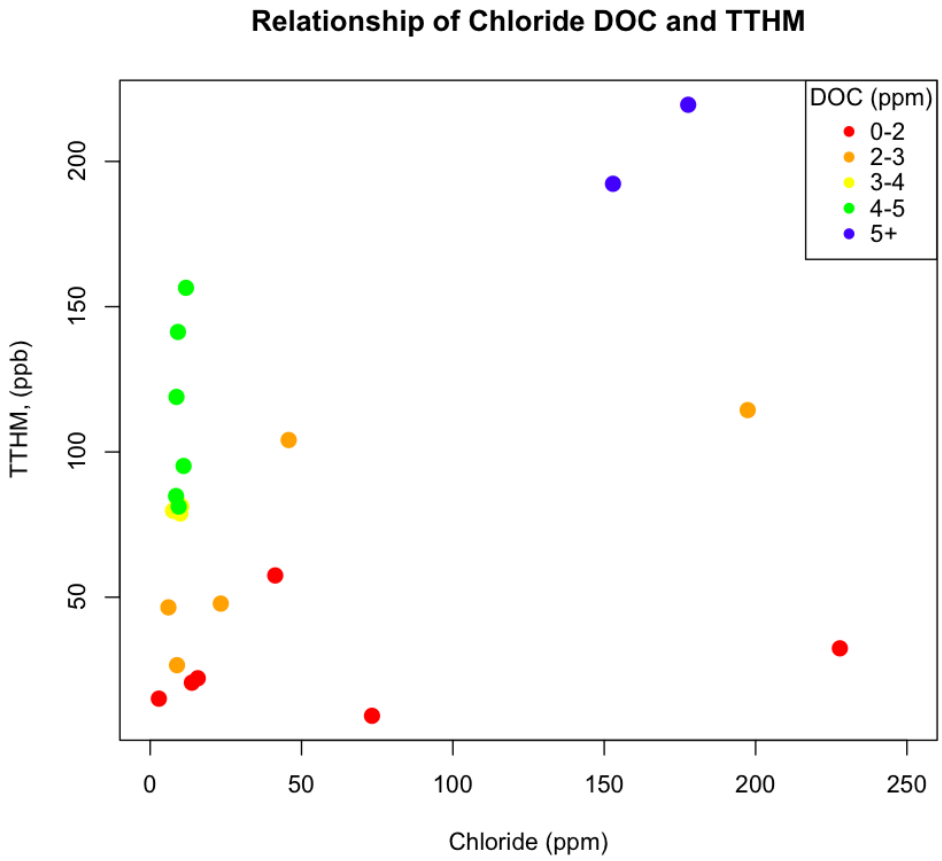

Figure 198: 18C displays the Chloride concentrations in relation to TTHM concentrations, organized by their total DOC concentration.

Bromide ions will outcompete to replace the chlorine atom in hypochlorous acid, transforming the oxidant into an even stronger hypobromous acid. Therefore, lower concentrations of bromide can produce higher proportionate concentrations of DBPs compared with chloride. We see a significant correlation between bromide and TTHM concentrations displayed in Figure 18a (R^2=0.2092, P-value=0.01248, F-statistic$_{23\text{-}1}$=7.347), which is consistent with the literature and chemical mechanisms. This may also explain why a correlation was found between chloride and TTHM concentrations; bromide and chloride are so highly correlated, the chloride/TTHM relationship may be secondary. We see a significant concentration between bromide and brominated haloforms as well in Figure 19b (R^2=0.6494, P-value <0.001, F-statistic$_{23\text{-}1}$=45.45). It should be noted that the range of bromide concentrations is substantially

smaller than that of chloride. From our data, many samples that contain 2 mg/L of bromide or less have TTHM concentrations above the EPA MCL.

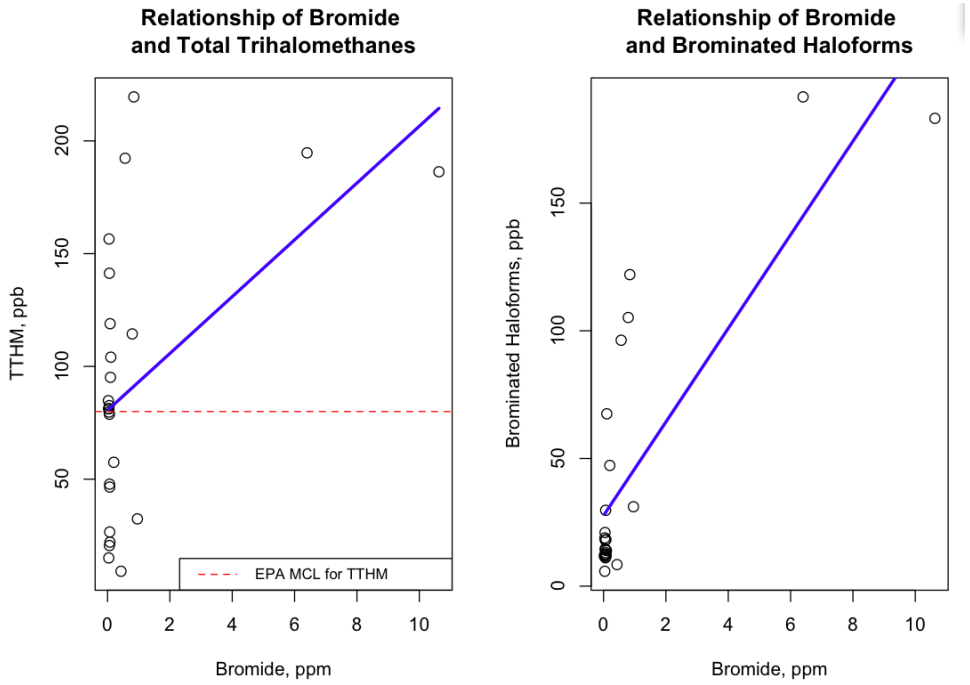

Figure 20: 19a: Relationship of bromide to TTHM concentrations. 19b: Relationship of bromide ion concentrations to brominated haloform concentrations.

Figure 20a displays the relationship of iodide and TTHM concentrations. A mildly significant correlation was found (R^2=0.2269, P-value=0.0145, F-statistic$_{20\text{-}1}$=7.163), which is consistent with the literature and chemical mechanisms as iodide is an even stronger oxidant than bromide. We did not, however, find a significant correlation between iodide and iodinated haloforms (R^2=0.07675, P-value=0.9646, F-statistic$_{20\text{-}1}$=0.002046). There are many potential explanations for this result. There is less iodide data, therefore the analysis is not as robust as for the previous halogens. Many samples with measurable quantities of iodide, also exhibited no quantifiable concentrations of iodinated DBPs. This may be due to the fact that in the presence of excess free chlorine, HOI is largely oxidized to iodate, an iodine sink, but in the presence of chloramines it is relatively stable. With chloramines, HOI is more likely to react with precursors producing the iodinated analogues than it would under chlorination. Since only chlorine was used to disinfect source water, this may explain why no correlation was found.

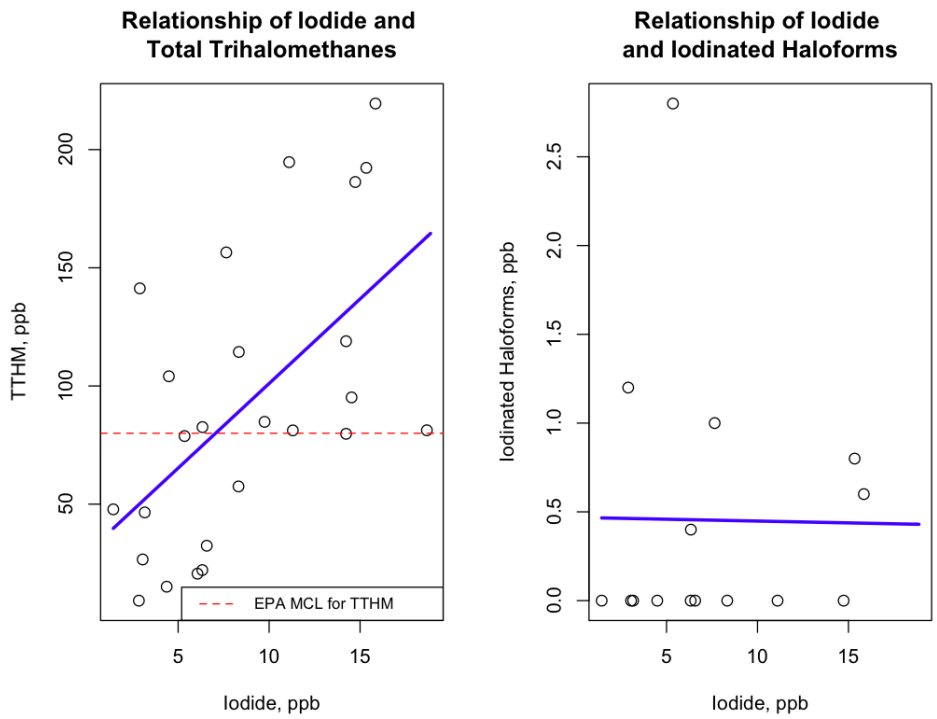

Figure 21: 20a: Relationship of Iodide to TTHM concentrations. 20b: Relationship of Iodide to total iodinated haloforms.

The relationship between TTHMs, dissolved organic carbon, ammonia, and conductivity was also examined. The role of organic matter in DBP formation is vastly more complex than halides, and mechanisms of action for this process are still unknown. However, literature has shown that organic matter can produce higher concentrations of dangerous DBPs than halides. A mildly significant correlation exists between DOC and TTHM (R^2=0.215, P-value=0.0149, F-statistic$_{21\text{-}1}$=7.025) shown in Figure 21a. The two sample points high in DOC come from utilities where the groundwater is pre-treated and may not be an accurate representation of the water that is being disinfected. While specific sources of organic matter in these groundwater samples is unknown, there are three main natural sources of organic matter to groundwater: organic matter deposits such as peat, soil and sediment organic matter, and organic matter present in waters percolating into the subsurface from surface water.

Sources of ammonium in groundwater can be anthropogenic or naturally-occurring, and concentrations can be indicative of decaying natural organic matter, and a reducing environment, which is present in these aquifers. Although coupled with DOC, we do not see a significant relationship between ammonium levels and TTHMs (R^2=-0.0176, P-value=0.4388, F-statistic$_{21\text{-}1}$=0.6228), in fact, the regression line is negative as displayed in Figure 21b. This is

understandable given that utilities attempting to chlorinate water with high ammonium levels could potentially be inadvertently chloraminating the water, which doesn't produce as many halogenated methanes, but does generate more haloacetic acids. Haloacetic acids were not quantified in our analysis and are not included in this project. This may be the cause for low levels of TTHMs, as well as higher levels of iodinated compounds in the Kill Devil Hills Well #3 sample, given it had the highest concentration of ammonium, 5.41 mg/L.

Electrical conductivity, the ability of a solution to transfer or conduct an electrical current, can be an indicator of dissolved ions in a solution. Conductivity is by no means a precursor, but its method of measurement is simple and could be used as a screening tool by utilities to identify water likely to produce DBPs during disinfection. A mild correlation was found between conductivity and TTHMs (R^2=0.1668, P-value=0.0336, F-statistic$_{21\text{-}1}$=5.205) as shown in Figure 21c; however in constructing a multiple linear regression using DOC and conductivity as two independent variables, the variation explained by the multiple regression was much higher (R^2=0.4629, P-value=0.006), as shown in Figure 22. Both of these measurement methods are relatively simple and efficient. By coupling them, utilities could use this model to more routinely test source water and more easily identify water that is of higher risk for DBP formation. With this information, utilities could implement techniques to prevent or mitigate DBP exceedances, or notify customers of potential DBP exposure.

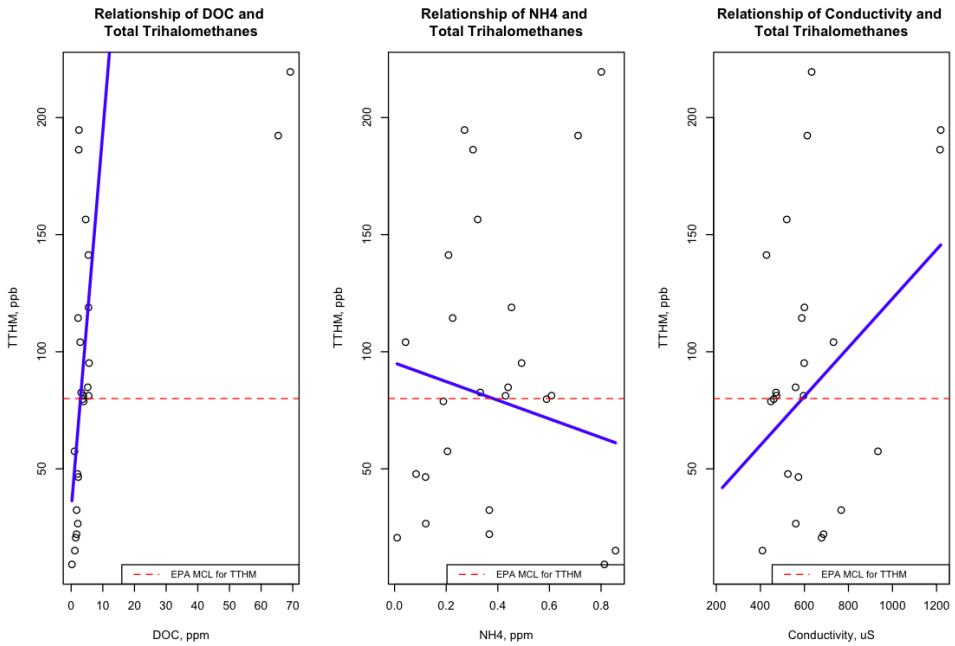

Figure 22: 21a: Relationship between DOC and TTHM concentrations. 21b: Relationship between ammonium and TTHM concentrations. 21c: Relationship between conductivity and TTHM concentrations.

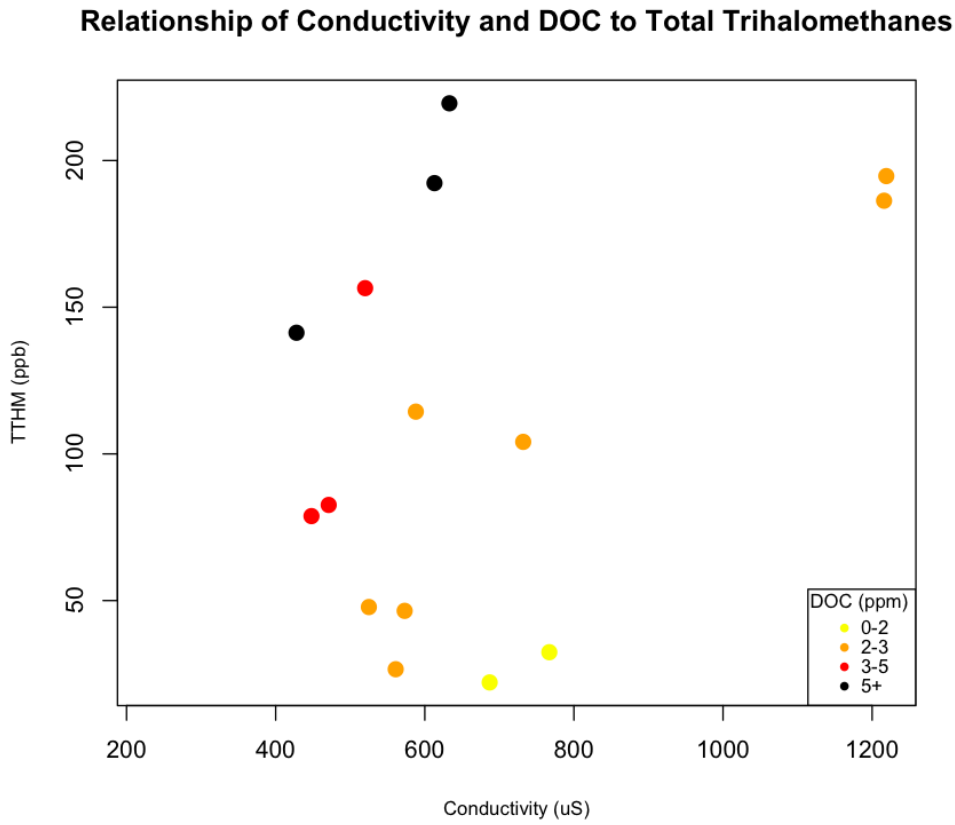

Figure 23: Multiple Linear Regression depicting the relationship between DOC and Conductivity to TTHM concentrations in raw groundwater samples.

Implications

Finally we come to the implications of this information for the customers of the utilities sampled. Bearing in mind that these are grab samples representing the concentration for a small fraction of time in the water system, two utilities presented with higher than allowable concentrations of the four measured DBPs in all of their wells. Given that there is no other water source for these utilities and that all the wells used by the utilities were tested, this represents a potential risk to over 80 ppb of DBPs for over 6,700 people receiving water from the Town of Beaufort and Harkers Island Sanitary District. Five additional utilities tested showed DBP levels greater than 80 ppb in at least one of their wells. Given the numbers of other wells, as well as information we cannot quantify including the mixing ratios and the wells received by each customer, we can only postulate that high levels of disinfection byproducts have the potential to affect over 160,000 people in the state, which amounts to over 11% of the population which relies on community drinking water from groundwater.

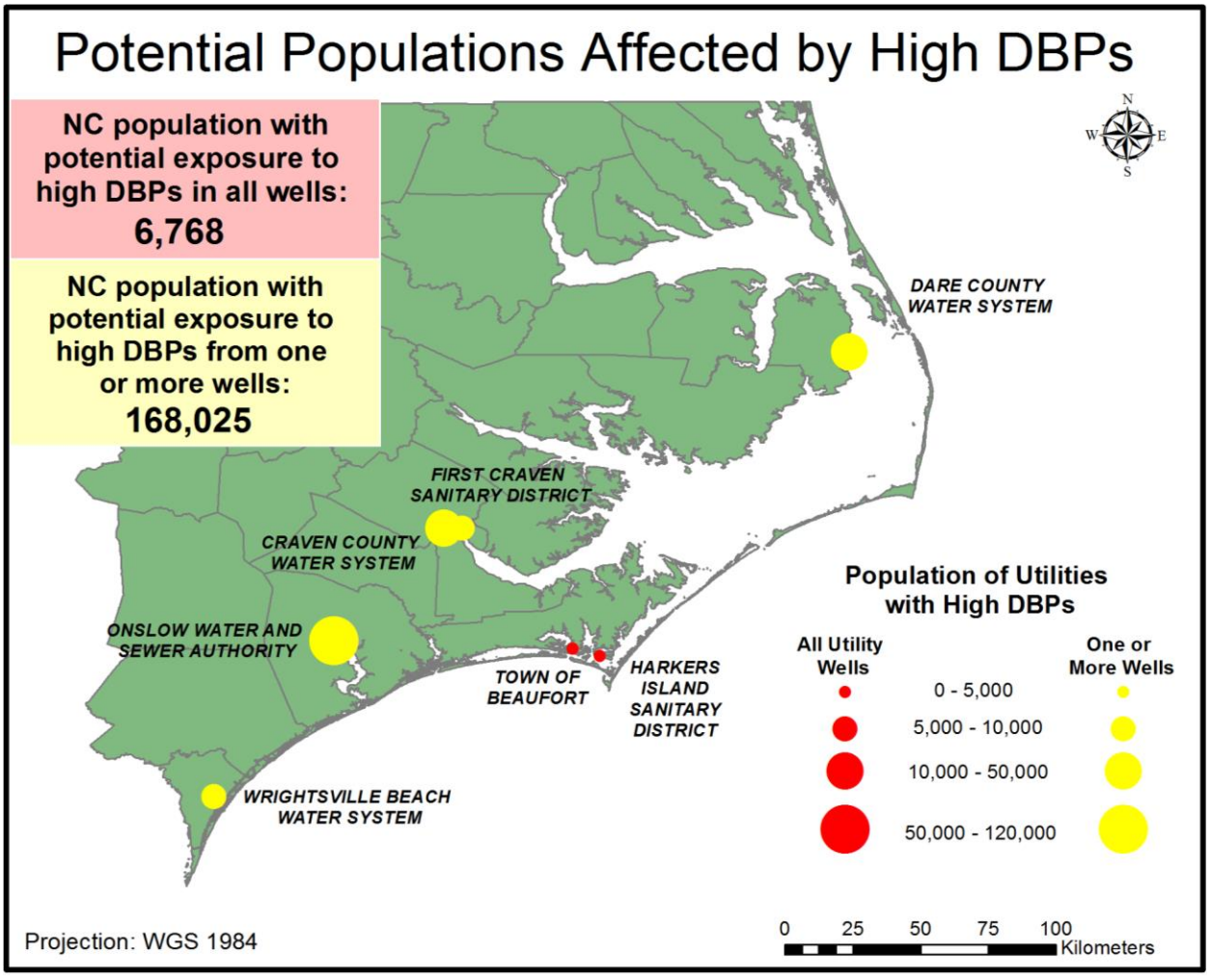

Figure 24: Potential exposure to DBPs from utilities whose well(s) tested above the EPA standard for drinking water.

As these are not the only groundwater utilities in the state of North Carolina, they might not be the only facilities and customers who could be at risk for higher than allowable levels of TTHMs in drinking water. The North Carolina Department of Environmental Quality has been working to generate maps dictating the fresh, salty, and transition zones of the aquifers of the Coastal Plain[25]. While these are a work in progress and their accuracy has not been independently verified, these maps serve as a starting point for characterizing additional areas of concern, as well as locations for future research.

Beginning with the Yorktown aquifer, there are four utilities which generated anywhere from 48-80 ppb of detected disinfection byproducts in their drinking water. Based on the previous studies of samples collected from the Yorktown, locations on the coast which could well be tapping saline water could be the most in danger of generating over 80 ppb of TTHMs in the future. Of particular concern would be the Belhaven Water System located in Beaufort County which is believed to be underlain by freshwater within the Yorktown aquifer, but the most recent TTHM concentration obtained was above 50 ppb. This salinity map does appear to align with the few samples which were collected, in that those in the freshwater zone do contain less than 250 ppm chloride ions, while samples collected from the transition zone are much more variable with concentrations above and below the 250 ppm threshold. The width of the transition zone, according to the department, corresponds to the dip of the freshwater-saltwater interface, and thus it is possible to encounter water with varying salinities at different depths.

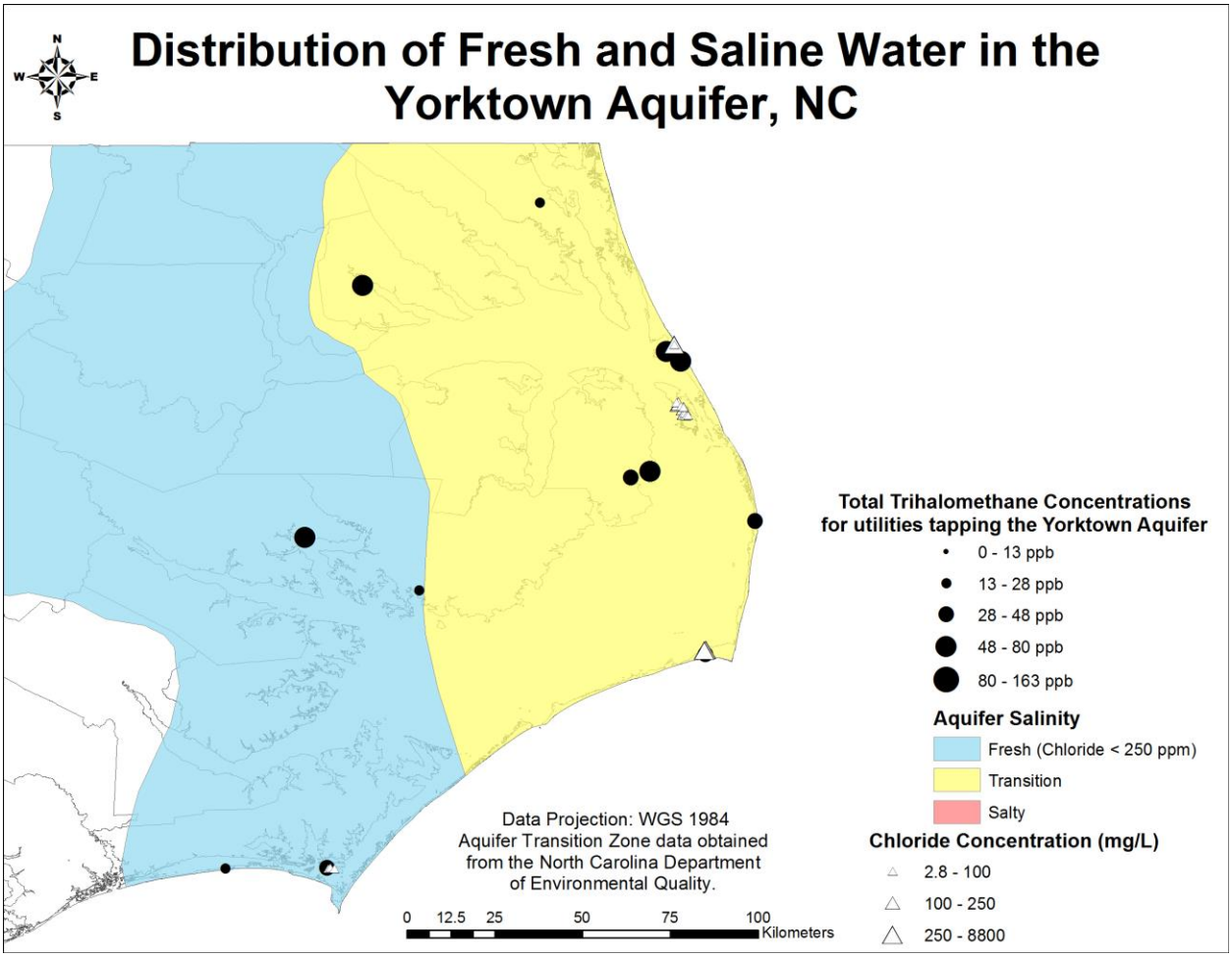

Figure 25: Yorktown Aquifer distribution[25] across North Carolina and potential utilities of concern based on most recent TTHM concentrations.

Comparing this to the Castle Hayne aquifer, the two are vastly different. The Castle Hayne is considered the most productive aquifer in the state, which corresponds to the map below which shows approximately 34 out of the 43 utilities mapped use this aquifer in some capacity. It also reflects some inaccuracies in the current state of this mapping process, with some utilities drawing water from beyond the boundaries, as well as multiple samples collected by the USGS which contain chloride concentrations higher than 250, the maximum believed to be present in the fresh water in that area.

For the most part, utilities tapping the Castle Hayne are reporting relatively low levels of TTHMs, with over 50% of utilities reporting concentrations from just above zero (the value representing information not reported or not available) to 28 ppb. Locations of concern or suggestions for future study within the Castle Hayne aquifer include the southernmost portion of the state of North Carolina and the transition map, where samples believed to be in freshwater

aquifers are reporting relatively high levels of TTHMs. More of a concern is the fact that USGS groundwater samples collected from the Castle Hayne here showed several locations with extremely high salt content, a fact that reinforces the need for more research and information regarding this all-important aquifer. Additionally, the Chowan County Water System is the only water system which could lie in the saline portion of the aquifer, and is indeed registering high levels of TTHMs, approaching the limit of 80 ppb.

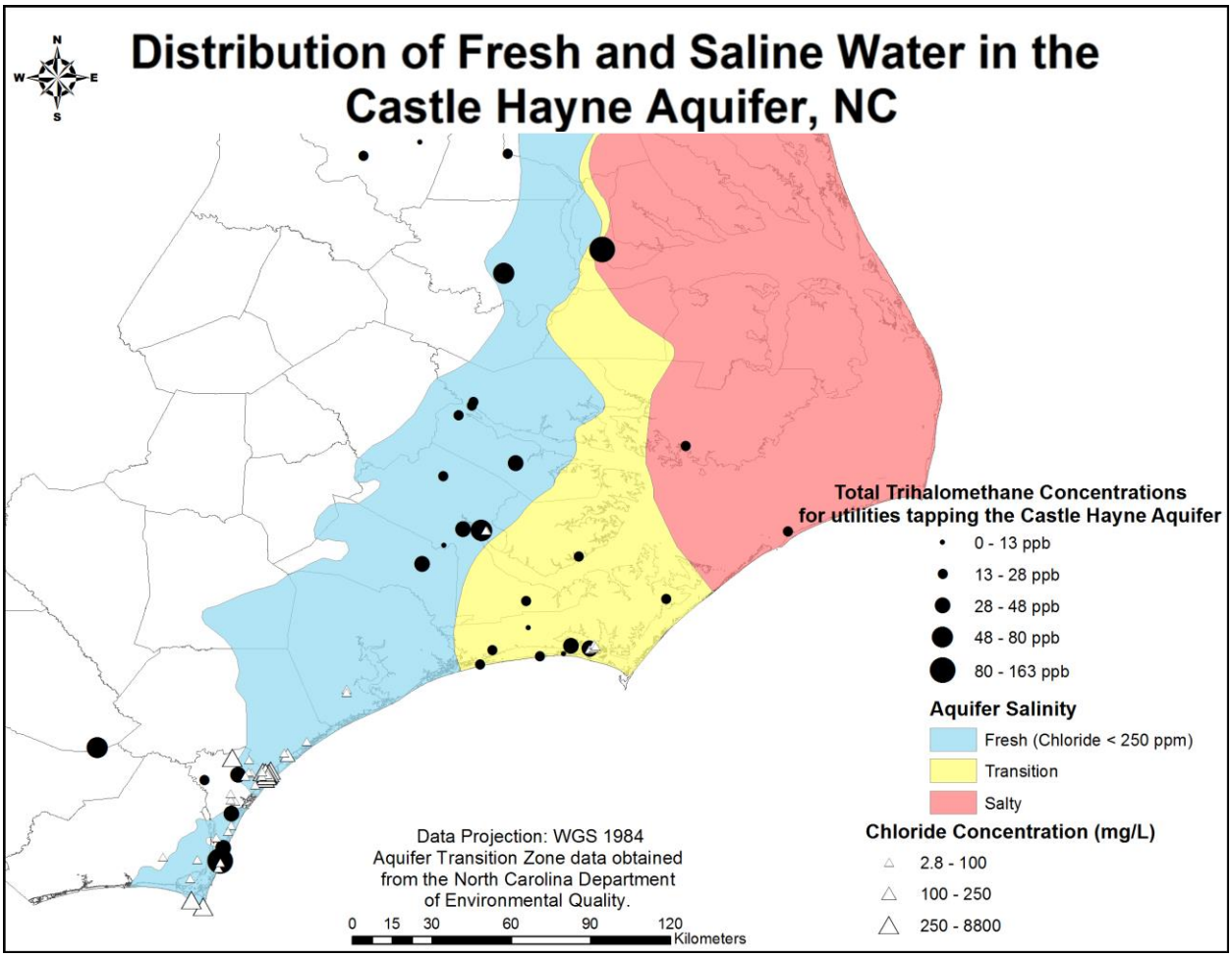

Figure 26: Castle Hayne Aquifer distribution[25] across North Carolina and potential utilities of concern based on most recent TTHM concentrations.

The utilities tapping the portion of the Peedee aquifer believed to be salty are the Craven County Water System and the Beaufort County Southside Water System. These systems, as well as the Wrightsville Beach and Town of Pender Water Systems could especially be at risk of higher halide concentrations in their drinking water as seawater continues to intrude into the freshwater portions of the aquifer. These systems are already experiencing over 40 ppb of

TTHMs in their water samples as well. It is also important to note that the Peedee, being a smaller aquifer between the Black Creek and Castle Hayne, two of the larger aquifers in this Coastal Plain system, the Peedee aquifer if often tapped in addition to other aquifers, which is the case for many of these systems. This makes characterizing the problem for particular utilities, as well as the future of their water supply, particularly difficult. The salinity boundaries mapped here match fairly well to the samples collected through the two most recent trips as well as those collected by the USGS. For the most part the samples lie within the transition zone, where depth of wells could play a role in the variability in chloride concentrations. Some of the wells with the highest chloride concentrations were those at approximately 100 feet or deeper, while several with lower concentrations were shallower, around 40-50 feet deep. However overall, the depth and salinity of this aquifer are extremely variable, as some wells with low chloride concentrations were around 160-170 feet deep[23].

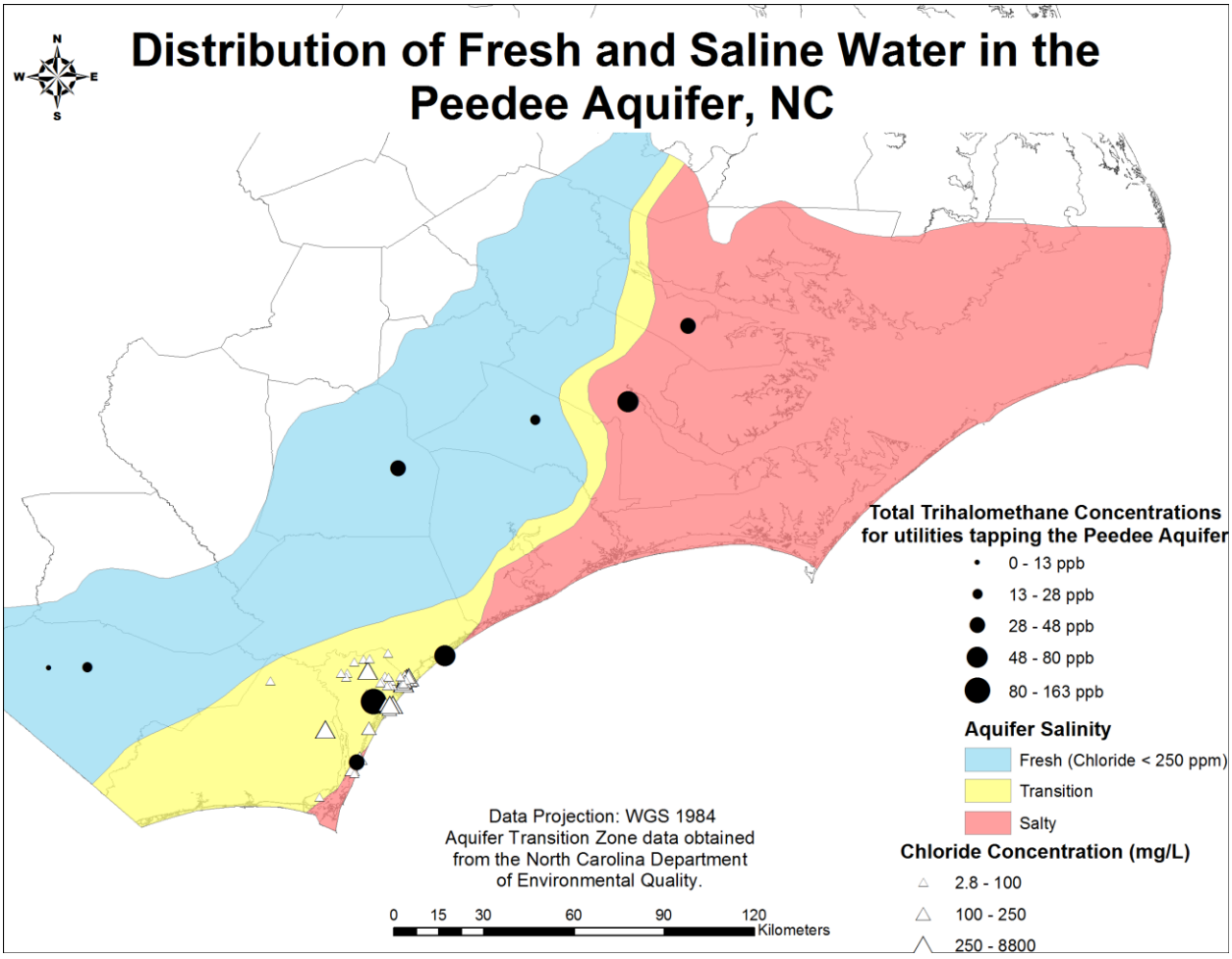

Figure 27: Peedee Aquifer distribution[25] across North Carolina and potential utilities of concern based on their most recent TTHM concentrations.

The Black Creek, while being the largest of the Cretaceous aquifer system, is also used in conjunction the other aquifers, typically the Cape Fear and Peedee. Utilities which have shown increased levels of TTHMs in their water systems include the Town of Pender, Onslow Water and Sewer, and the Town of Williamston. Of particular concern are the utilities in the Town of Williamston as well as those in Bladen and Columbus Counties. While many of these draw from other aquifers in addition to the Black Creek, they lie well within what previous research has generalized as within the freshwater boundary of the Black Creek, yet some utilities are reporting TTHM concentrations above 50 ppb. These salinity boundaries do not conflict with samples collected for the Black Creek aquifer. While samples collected in the transition zone had low chloride concentrations, they could have been at an appropriate depth to draw fresh water. Additionally, the only high chloride sample collected from the Black Creek was to the North in the town of Williamston, however that value was not above the 250 ppm designation for fresh water.

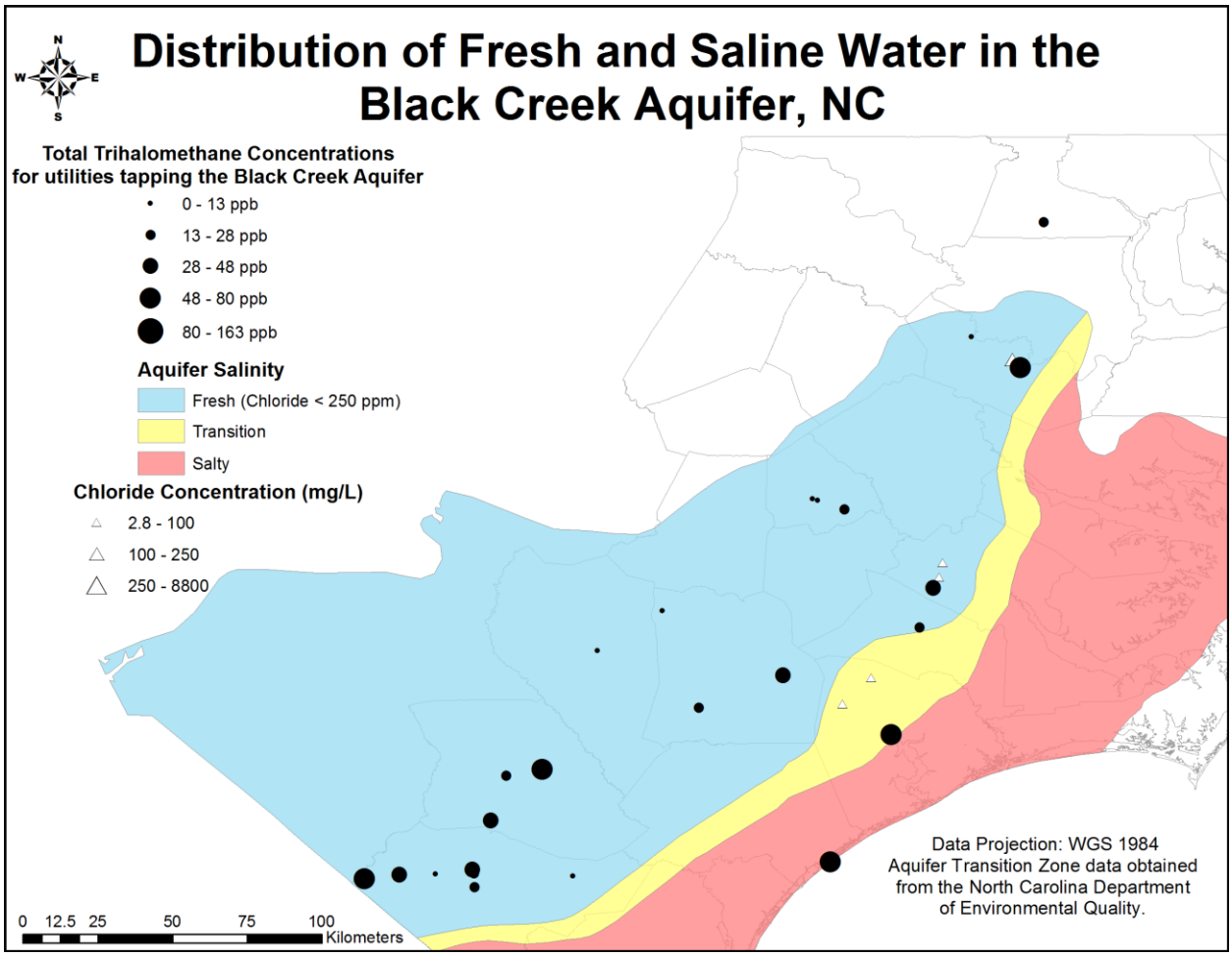

Figure 28: Black Creek Aquifer distribution[25] across North Carolina and potential utilities of concern based on their most recent TTHM concentrations.

Many utilities which draw from the Cape Fear aquifers also tap the Black Creek aquifer, and the bulk of that overlap is demonstrated here. Additional locations or utilities of concern aside from those previously mentioned include the Town of Windsor, which recently reported TTHM concentrations above 50 ppb. The chloride concentrations for samples collected from the Cape Fear also correspond to the salinity boundaries characterized by the Department of Environmental Quality. Samples were collected from fresh groundwater and transition zones, and no samples tested above 100 ppm of chloride. While this means that no action needs to be taken to reduce the salinity of the groundwater prior to consumption, as the previous statistical analyses as well as the utility data have shown that chloride levels above the designation for fresh water are not necessary to produce dangerous levels of disinfection byproducts.

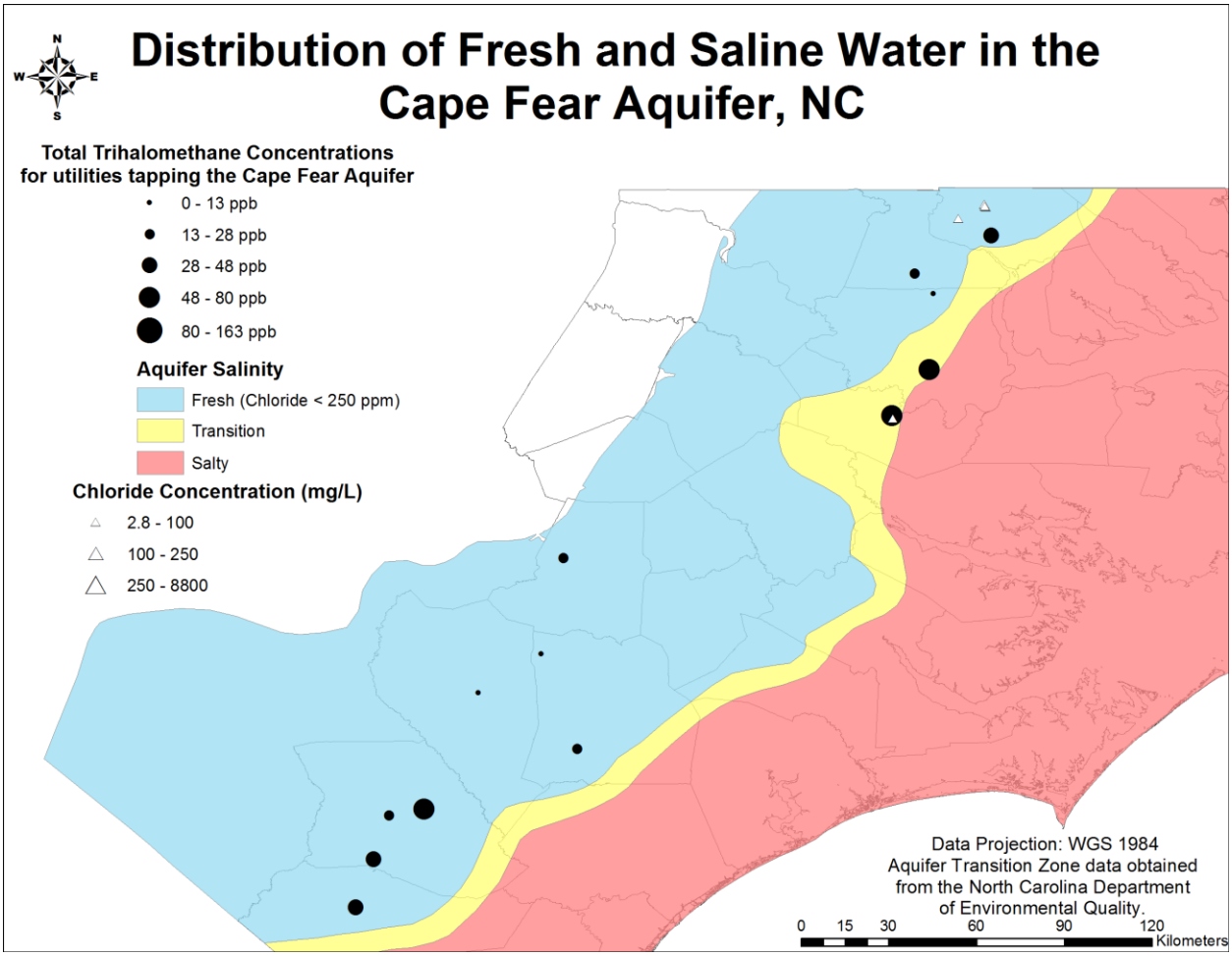

Figure 29: Cape Fear Aquifer distribution[25] across North Carolina and potential utilities of concern based on their most recent TTHM concentrations.

Source Water and Monitoring Samples

Monitoring samples were collected for the purpose of observing the concentrations of chemical constituents pre- and post-disinfection. Not only can they provide information regarding the proportions of each well being used for drinking water at the time, but they also highlight additional treatment in some cases, and inconsistencies in others. Given that our analysis is conducted through the lens of disinfection byproduct formation, the comparison below displays chloride, bromide, iodide, DOC and ammonium concentrations, all prominent chemical factors in DBP formation.

Working down the list, Wrightsville Beach clearly starts with more saline groundwater with chloride levels well above the EPA standard of 250 mg/L in Well #1 and Well #8, but their final consumptive product is well within the chloride standard. The same can be said for the First Craven Sanitary District, where little work is necessary to remove chloride from the system and the monitoring sample concentrations are very similar to both Wells #1 and #2.

Initially taking a sample of source groundwater from Kill Devils Hills (Well #3) proved ineffective because the chloride value was clearly too high and not representative of the water being disinfected. The RO permeate (post-RO, pre-disinfection) showed much lower chloride and bromide concentrations. The monitoring sample however, showed chloride levels higher than the EPA standard, and in both tests, relatively high bromide concentrations compared to samples from some of the other utilities. Considering that not all of Kill Devil Hills wells may have high enough ion concentrations to warrant Reverse Osmosis, this could be the result of mixing between wells prior to entering the distribution system.

The Town of Williamston showed large variation between the two wells we sampled. They collect groundwater from a total of eight wells, so again the high levels could be the result of mixing with other higher chloride groundwater. Regardless, the monitoring sample showed chloride levels much higher than the EPA standard, and aside from the pre-RO sample from Kill Devil Hills, the second highest bromide concentrations of any of the water samples. Harker's Island Sanitary District uses two groundwater wells for their potable water. The monitoring sample shows slightly elevated chloride values compared to either well, but not by an order of magnitude.

Craven County utilizes 10 wells for their drinking water, and the monitoring sample shows that Well #5, or other wells with similar chloride concentrations made up the majority of

the drinking water provided in that sample. The monitoring sample collected on the Onslow Water and Sewer Distribution system tested much higher, yet not over the limit of chloride compared to all of the source groundwater samples collected. This could be a characteristic of the sampling location rather than the raw groundwater. The Town of Beaufort samples show reasonable source and monitoring sample levels of chloride and bromide.

Samples of raw groundwater were collected from each of the wells used by the Gates County Water System. Based on that information, Gates County likely uses a larger percentage of water from Well #1 than either Well #2 or Well #3.

Table 2: Comparison of source water and monitoring sample geochemistry.

Sample ID	IC (mg/L)		ICP-MS	TOC (mg/L)		Laboratory Conductivity (µS)
	Cl	Br	I (µg/L)	NH4-N	DOC	
Wrightsville Beach Well #1	1433.55	10.63	14.74	0.30	2.40	1216.00
Wrightsville Beach Well #7	197.39	0.79	8.34	0.23	2.20	588.00
Wrightsville Beach Well #8	1464.67	6.40	11.10	0.27	2.47	1218.00
Wrightsville Beach Monitor	14.88	0.04	11.10	0.01	2.83	227.50
First Craven Sanitary District Well #1	9.17	0.05	6.34	0.33	3.18	471.10
First Craven Sanitary District Well #2	11.83	0.05	7.65	0.32	4.60	520.00
First Craven Sanitary District Monitor	14.24	0.06	6.30	0.01	3.35	462.80
Dare County Skyco Well #13	152.89	0.56	15.34	0.71	65.39	613.00
Dare County Skyco Well #4	177.73	0.84	15.85	0.80	69.23	633.00
Dare County Kill Devil Hills Well #3	2712.27	12.42	152.70	5.41	78.55	7160.00
Dare County Kill Devil Hills RO Permeate	73.28	0.43	2.84	0.81	0.26	268.80
Dare County Kill Devil Hills Monitor	424.41	0.57	8.30	0.01	1.15	631.00
Dare County Kill Devil Hills Monitor 2	422.98	1.25	N/A	N/A	N/A	N/A
Town of Williamston Well #8	227.84	0.96	6.57	0.37	1.72	767.00
Town of Williamston Well #4	15.73	0.08	6.33	0.37	1.72	687.00
Town of Williamston Monitor	623.22	3.38	10.60	0.01	1.88	1033.00
Harkers Island Sanitary District Well #1	10.26	0.04	18.67	0.61	3.87	467.30
Harkers Island Sanitary District Well #2	7.55	0.05	14.23	0.59	3.62	459.60
Harkers Island Sanitary District Monitor	24.04	0.05	18.87	0.01	3.51	466.60
Craven County Well #5	45.76	0.10	4.49	0.04	2.86	732.00
Craven County Well #2	23.33	0.07	1.43	0.08	2.03	525.00
Craven County Monitor	49.57	0.05	3.95	0.01	2.35	664.00
Onslow Water and Sewer Authority Well #6	6.02	0.07	3.16	0.12	2.26	573.00
Onslow Water and Sewer Authority Well #2	8.87	0.07	3.05	0.12	2.11	561.00
Onslow Water and Sewer Authority Well #D7	9.96	0.06	5.35	0.19	3.96	448.00
Onslow Water and Sewer Authority Well #D5	9.18	0.06	2.89	0.21	5.44	427.90
Onslow Water and Sewer Authority Monitor	242.37	0.72	5.75	0.01	2.62	839.00
Town of Beaufort Well #2	8.54	0.03	9.75	0.44	5.23	568.00
Town of Beaufort Well #3	9.44	0.03	14.23	0.45	5.47	616.00
Town of Beaufort Well #4	11.03	0.09	14.53	0.49	5.66	595.00
Town of Beaufort Well #5	8.69	0.08	11.30	0.43	5.53	591.00
Town of Beaufort Monitor	16.75	0.08	10.90	0.09	5.60	607.00
Gates County Water System Well #1	41.31	0.20	8.32	0.21	1.07	921.00
Gates County Water System Well #2	2.87	0.04	4.37	0.86	1.17	408.50
Gates County Water System Well #3	13.77	0.06	6.06	0.01	1.45	676.00
Gates County Water System Monitor	40.72	0.12	8.25	0.01	1.19	818.00

The results of simulated disinfection (in TTHMs, ppb) were also compared to the values obtained by the nine selected drinking water utilities for the most recent year. With the exception of the Town of Beaufort and Harkers Island, all other utilities have more wells than were sampled, and so without specific knowledge of the locations and source water for the portion of the distribution system sampled, it is unclear whether the water which utilities test to record TTHM concentrations ever came from any wells which we sampled. Given the table above there can be a great deal of variation between source water and combined samples. Additionally, the simulated DBP samples were collected as a grab sample, as do water utilities. Water composition and chemical concentrations are extremely varied, and this will vary throughout the aquifer and correspondingly throughout the distribution system.

The table below shows that for each utility, the most recent TTHM value in water quality report is very different, by at least 15 ppb for each well sampled. Only eight of the samples disinfected generated TTHM concentrations less than their previously reported values. The rest were higher, and this can be due to a variety of reasons. In the case of the Skyco source water samples, these are naturally more saline and contain higher amounts of organic matter, hence their water is treated to remove these precursor to form smaller amounts of byproducts in their water. For others, such as Onslow Water and Sewer, which draws water from approximately 37 wells, a small portion if any of the water which we sampled and disinfected may make it to the point in the distribution system which is tested by the utility.

Table 3: Comparison of reported and measured TTHM values.

Water System Name	Most recent TTHM recorded, ppb	Well Number	Laboratory Measured TTHM value, ppb
Town of Beaufort	39	Well #2	84.8
		Well #3	81.2
		Well #4	95.2
		Well #5	118.9
Harkers Island Sanitary District	37	Well #1	81.3
		Well#2	79.8
Craven County Water System	63	Well #2	47.8
		Well #5	104.1
First Craven Sanitary District	66	Well #1	83
		Well #2	157.5
Dare County Water System	52	Skyco Well #4	220.1
		Skyco Well #13	193.1
		Kill Devil Hills Well #3	25.1
		Kill Devil Hills RO Permeate	9.2
Gates County Water System	42	Well #1	57.5
		Well #2	15.1
		Well #3	20.6
Town of Williamston	69	Well #4	22.1
		Well #8	32.4
Wrightsville Beach Water System	83	Well #1	186.3
		Well #7	114.4
		Well #8	194.7
Onslow Water and Sewer Authority	62	Well #2	26.6
		Well #6	46.5
		Well #D5	142.5
		Well #D7	81.6

Solutions to reduce DBP formation in Drinking Water

There are several physical methods to remove organic matter and halides from drinking water. Membrane technologies include Reverse Osmosis, Nanofiltration, and Electrodialysis/Electrodialysis reversal, as well as variations on these methods[26]. Reverse Osmosis has the highest salt rejection rate of all the methods, and removes organic matter, however it is the most expensive. Dare County has a reverse osmosis plant in Kill Devil Hills, and between our grab samples of raw groundwater and the RO combined water, saw a 99.93% removal of Bromide. Nanofiltration is second in its ability to remove bromide and iodide, but not by much. Most membranes are capable of removing organic matter, but it is dependent on the molecular-weight cutoff of the membrane. Both of these systems require extensive pre-treatment of water, and consume copious amounts of energy, however nanofiltration doesn't require as high water pressures, meaning it uses less energy and can operate at slightly lower cost[26]. Because nanofiltration can generate greater water recovery, less waste is generated. For these reasons, Nanofiltration is becoming an increasingly popular method. Electrodialysis is not typically used in water treatment systems, but has had several successful implementations[26]. While it does not remove organic matter, it is effective at reducing ions in solution[26, 27].

Other adsorptive methods include using various forms of activated carbon or ion exchange resins[27]. The most effective forms of activated carbon typically contain other compounds, and silver chloride has been found to remove up to 98% of iodide in experiments and can also remove organic carbon as well, at a lower cost than either Reverse Osmosis or Nanofiltration[26]. Ion exchange can occur using a resin or a membrane, are capable of removing organic matter, and are less expensive than Reverse Osmosis and Nanofiltration, however they are less effective at ion removal than these counterparts. Typical experiments have indicated up to 60% removal of bromide in solution[26].

Another option is to alter the method of disinfection entirely. Some of the raw water samples were disinfected via chlorination and chloramination and exhibited on average a 96.5% decrease in total trihalomethane formation. Chloramination is the second most common method of treatment in the U.S., however, it stabilizes the formation of hypoiodic acid, which generates higher concentrations of iodinated disinfection byproducts. Chloramination, however, comes with its own host of issues, including the increased formation of haloacetic acid DBPs. This is one of the many tradeoffs and considerations to make before a utility would switch disinfection

systems. While there is little information based on these collected samples regarding the effectiveness of reducing ions or organic carbon at reducing concentrations of DBPs formed, the statistics speak to a relationship between conductivity and dissolved organic carbon which would suggest that if methods are established to remove these precursors to DBP formation, lower concentrations of TTHMs could be generated as a result.

Uncertainties

There are several uncertainties associated with our research which should be noted in this report. First, high ammonia levels were detected in some of raw samples, up to the point where disinfection simulation via just chlorination was impossible. Adding chlorine to water with high ammonia levels could actually be causing inadvertent chloramination of the water, a different chemical process that produces different DBPs (mainly an increase in haloacetic acids and decrease in trihalomethanes). This could be occurring in some of our samples and could be affecting the TTHM results we see. Unfortunately, quantifying haloacetic acids was out of the scope of our project, but would be necessary for investigating thresholds for these chemical processes.

In our study design, we elected to collect grab samples of water which is constantly flowing. This sampling method only represents one point in time, so we have not accounted for seasonal or production variability in our current research. While this makes comparison to single samples collected by utilities for their water quality reports, as well as our own monitoring samples difficult, we are operating under the same sampling ideology as utilities in determining the geochemical composition of their water supply. Some of the utilities we collected samples from also pre-treat the raw groundwater, whether it be aeration, softening, filtering, or processes to reduce halide and organic matter levels, like reverse osmosis. Our samples are of the raw groundwater and not the pre-treated water to characterize the geochemistry of aquifers and conduct a spatial analysis, and the pre-treated water would contain mixture of all the wells in use.

We also acknowledge a relatively small sample size, and the amount of samples per aquifer was even smaller. To improve the power of our analyses, additional sampling is needed.

Conclusion

15 out of 26 collected samples were found to exceed the EPA MCL of 80 ppb for Total trihalomethane Concentrations. Although this is just a snapshot in time, it is still alarming that these chemicals are so prevalent in the North Carolina Coastal Plain. Because the Coastal Plain extends most of the Eastern seaboard, it is possible that groundwater-dependent coastal communities within a broader range could be experiencing higher levels of DBP formation and subsequent exposure.

Based on our data, halide concentrations in groundwater samples are most likely a result of saltwater intrusion, as the Cl/Br plots show an approximate following to the seawater intrusion line. Although different aquifers could be experiencing salinization at different rates, this finding is important because projected sea level rise and increased water usage will only quicken salinization of these aquifers. Increasing concentrations of halides, especially bromide and iodide which are generally associated with seawater in higher concentrations, may increase potential DBP formation. These results suggest that the EPA may need to establish MCLs for DBP precursors as part of a public health effort to reduce population-wide exposures of potential carcinogens.

It can also be concluded that water treatment should be both aquifer and location specific, due to the intra-aquifer chemical variability. Some utilities have already implemented pre-treatment techniques to prevent DBP formation or, in Dare County's case, to mitigate DBP formation. Dare County, whose raw wells had some of the highest halide and organic matter concentrations, has an extensive system of both Reverse Osmosis and Ion Exchange to pre-treat water before disinfection. Dare County draws from the Yorktown aquifer, which in that specific area, is very saline. However, processes like these would not be necessary at other utilities that are not dealing with as high of levels as Dare County. Possibly the most important finding is the relationship between conductivity, dissolved organic carbon, and TTHM formation. Conductivity and DOC measurement methods are relatively cheap and efficient. By establishing a threshold for these parameters, utilities could potentially use these methods in concert with one another to identify raw water that is likely to exceed the MCL once disinfected. Water could be tested via this method more frequently than DBPs are tested for, and could contribute to the prevention of so many exceedances.

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Appendices

Appendix A. Raw data tables.

Lab ID	Sample ID	THM (ug/L)								
		TCM	BDCM	DBCM	TBM	DCIM	BCIM	DBIM	CDIM	BDIM
NH-01	NH_WELL#1	3.1	13	50.3	119.9					
NH-07	NH_07_WELL#7	9.2	23.1	46.6	35.5					
NH-08	NH_WELL#8	3.1	15.8	60.9	114.9					
CR-F-01	CRAVEN_FIRST_WELL#1	64.6	15	3		0.4				
CR-F-02	CRAVEN_FIRST_WELL#2	135.5	18.9	2.1		1				
SKY-13	SKYCO_WELL#13	96	60	33.5	2.8	0.8				
SKY-04	SKYCO_WELL#4	97.5	69.9	46.2	5.9	0.6				
KDH-03	KDH_WELL#3	0.7	3.1	5.2	16.1			8.9	0.9	12.3
MA-08	MARTIN_WELL#8	1.3	4.8	11.8	14.5					
MA-04	MARTIN_WELL#4	3.9	6.7	8.3	3.2					
CR-CO-05	CRAVEN_CO_WELL#5	36.6	30.7	29	7.8					
CR-CO-02	CRAVEN_CO_WELL#2	18.1	15.7	12.2	1.8					
ON-06	ONSLOW_WELL#6	34	10.6	1.9						
ON-02	ONSLOW_WELL#2	13.5	8.6	4.2	0.3					
ON-D7	ONSLOW_WELL#D7	68.1	9.7	1		1	1.8			
ON-D5	ONSLOW_WELL#D5	130.2	10.5	0.6		1.2				
2	CARTERET_WELL#2	73	10	1.2	0.2					
3	CARTERET_WELL#3	69	11	1.4	0.2					
4	CARTERET_WELL#4	81	12	1.5	0.2					
5	CARTERET_WELL#5	107	11	0.9	0.1					
7	GATES_WELL#1	10	17	22	8					
8	GATES_WELL#2	9.2	3.9	1.7	0.2					
9	GATES_WELL#3	6.3	7.1	6.1	1.0					
11	HARKERS_WELL#1	62	16	2.9	0.2					
12	HARKERS_WELL#2	65	13	1.6	0.1					
KDH_RO	13	0.7	2.0	3.6	2.9					

Lab ID	Sample ID	Alkalinity (mg/L)
		HCO3-
NH-01	NH_WELL#1	256
NH-07	NH_07_WELL#7	237
NH-08	NH_WELL#8	254
NH-M	NH_MONITOR	40
CR-F-01	CRAVEN_FIRST_WELL#1	296
CR-F-02	CRAVEN_FIRST_WELL#2	327
CR-F-M	CRAVEN_FIRST_MONITOR	276
SKY-13	SKYCO_WELL#13	322
SKY-04	SKYCO_WELL#4	335
KDH-03	KDH_WELL#3	383
KDH-M	KDH_MONITOR	98
MA-08	MARTIN_WELL#8	352
MA-04	MARTIN_WELL#4	406
MA-M	MARTIN_MONITOR	373
CR-CO-05	CRAVEN_CO_WELL#5	371
CR-CO-02	CRAVEN_CO_WELL#2	283
CR-CO-M	CRAVEN_CO_MONITOR	327
ON-06	ONSLOW_WELL#6	395
ON-M	ONSLOW_MONITOR	417
ON-02	ONSLOW_WELL#2	356
ON-D7	ONSLOW_WELL#D7	132
ON-D5	ONSLOW_WELL#D5	263
1	CARTERET_M	476
2	CARTERET_WELL#2	359
3	CARTERET_WELL#3	406
4	CARTERET_WELL#4	424
5	CARTERET_WELL#5	417
6	GATES_M	482
7	GATES_WELL#1	551
8	GATES_WELL#2	273
9	GATES_WELL#3	439
10	HARKERS_M	302
11	HARKERS_WELL#1	313
12	HARKERS_WELL#2	313
KDH_RO	13	13
KDH_3R	14	N/A

Lab ID	Sample ID	TOC (mg/L)	
		NH4-N	DOC
NH-01	NH_WELL#1	304	2.4
NH-07	NH_07_WELL#7	0.225	2.198
NH-08	NH_WELL#8	0.271	2.474
NH-M	NH_MONITOR	<0.01	2.829
CR-F-01	CRAVEN_FIRST_WELL#1	0.332	3.175
CR-F-02	CRAVEN_FIRST_WELL#2	0.322	4.599
CR-F-M	CRAVEN_FIRST_MONITOR	<0.01	3.354
SKY-13	SKYCO_WELL#13	0.711	65.39
SKY-04	SKYCO_WELL#4	0.801	69.23
KDH-03	KDH_WELL#3	5.41	78.55
KDH-M	KDH_MONITOR	<0.01	1.148
MA-08	MARTIN_WELL#8	0.367	1.722
MA-04	MARTIN_WELL#4	0.367	1.722
MA-M	MARTIN_MONITOR	<0.01	1.881
CR-CO-05	CRAVEN_CO_WELL#5	0.0425	2.863
CR-CO-02	CRAVEN_CO_WELL#2	0.0833	2.027
CR-CO-M	CRAVEN_CO_MONITOR	<0.01	2.348
ON-06	ONSLOW_WELL#6	0.12	2.258
ON-M	ONSLOW_MONITOR	<0.01	2.62
ON-02	ONSLOW_WELL#2	0.121	2.106
ON-D7	ONSLOW_WELL#D7	0.189	3.963
ON-D5	ONSLOW_WELL#D5	0.209	5.443
1	CARTERET_M	0.093	5.6
2	CARTERET_WELL#2	0.44	5.232
3	CARTERET_WELL#3	0.43	5.531
4	CARTERET_WELL#4	0.492	5.656
5	CARTERET_WELL#5	0.453	5.468
6	GATES_M	0.011	1.187
7	GATES_WELL#1	0.205	1.073
8	GATES_WELL#2	0.856	1.172
9	GATES_WELL#3	<0.01	1.449
10	HARKERS_M	0.011	3.513
11	HARKERS_WELL#1	0.608	3.867
12	HARKERS_WELL#2	0.589	3.619
KDH_RO	13	0.813	0.256

Lab ID	Sample ID	DCP (mg/L)							
		Ca	Mg	Sr	Na	Fe	Ba	Mn	Si
NH-01	NH_WELL#1	54.59664275	1.690548571	0.050243481	0.885129073	6.258537641	2.87456E-07	0.093667344	0.065997611
NH-07	NH_07_WELL#7	52.43562632	13.43432645	0.296065426	48.03991855	0.038882221	0.004448767	0.001601556	9.093679583
NH-08	NH_WELL#8	85.80905705	21.40437713	0.463593714	122.9582734	0.037920158	0.000243468	0.089839732	9.464518429
NH-M	NH_MONITOR	8.23539	2.27504	0.04839	29.32674	ND	0.02296	0.01168	3.88312
CR-F-01	CRAVEN_FIRST_WELL#1	54.41200562	8.95169407	0.315537887	33.19453285	0.645212044	0.000360313	0.057469884	17.7181994
CR-F-02	CRAVEN_FIRST_WELL#2	62.08560154	10.11846621	0.363670849	35.08449621	0.775337335	0.000393299	0.063308094	21.62036307
CR-F-M	CRAVEN_FIRST_MONITOR	12.27865443	2.003798648	0.036008376	0.781336651	16.06056286	5.44338E-08	0.239167001	0.225847301
SKY-13	SKYCO_WELL#13	58.25179614	8.679610582	0.367838175	58.88145385	0.367731116	0.005108226	0.098172768	13.00880177
SKY-04	SKYCO_WELL#4	31.73054726	1.977869245	0.04847588	1.007042841	5.660351502	2.78357E-07	0.092929101	0.10624955
KDH-03	KDH_WELL#3	184.3967874	0.106607635	0.151178081	0.532712555	6.449692963	1.47669E-07	0.195307439	0.017012269
KDH-M	KDH_MONITOR	19.11879061	0.981450871	0.047475151	0.843882962	4.01720594	7.71696E-08	0.273288541	0.033364975
MA-08	MARTIN_WELL#8	11.96305977	0.178938281	0.006812804	0.530611993	21.9553643	5.17426E-08	0.283749784	0.058824847
MA-04	MARTIN_WELL#4	11.4721053	0.198626751	0.006770045	0.530611993	21.9553643	5.17426E-08	0.283749784	0.058824847
MA-M	MARTIN_MONITOR	17.85498495	0.113687967	0.005402778	0.512339083	7.722947281	2.14599E-08	0.520822749	0.022625919
CR-CO-05	CRAVEN_CO_WELL#5	11.43220802	0.245815238	0.010896532	0.652942305	15.46953933	3.21363E-08	0.381986541	0.045626815
CR-CO-02	CRAVEN_CO_WELL#2	9.593283318	0.174486912	0.004416083	0.428325805	6.375689143	2.83245E-08	0.159900109	0.032572268
CR-CO-M	CRAVEN_CO_MONITOR	10.80119697	0.216576377	0.008378016	0.672994872	8.200305303	1.76019E-08	0.470111831	0.028049739
ON-06	ONSLOW_WELL#6	9.44472462	0.22845723	0.006321638	0.622942078	3.683716429	7.6732E-09	0.580791281	0.017452884
ON-M	ONSLOW_MONITOR	12.81620511	0.155651163	0.006492496	0.674690039	5.410561673	7.8771E-09	0.578659787	0.018760545
ON-02	ONSLOW_WELL#2	12.33565861	0.233133557	0.006001077	0.484669121	8.759499068	2.10628E-08	0.228710377	0.045419988
ON-D7	ONSLOW_WELL#D7	68.55512911	5.021908486	0.333930001	11.77591855	2.215955676	0.004323226	0.159903358	26.10823001
ON-D5	ONSLOW_WELL#D5	65.48524824	4.433031433	0.22096954	8.955291262	0.130945709	0.003547208	0.05181073	21.92379655
1	CARTERET_M	21.99731071	8.831310946	0.229042046	113.2228476	0.041367142	0.013360531	0.027608703	22.60555921
2	CARTERET_WELL#2	75.87200152	18.77901367	0.676372065	18.61663453	0.083528037	0.012556677	0.028610999	20.41175697
3	CARTERET_WELL#3	68.27248052	28.13899951	0.627289661	17.41306805	0.037075556	0.014914077	0.028555366	20.38709367
4	CARTERET_WELL#4	70.68691585	25.2442458	0.644791604	16.92130498	0.078331954	0.015227091	0.033259172	20.27248193
5	CARTERET_WELL#5	75.16853507	28.6016766	0.725294431	21.34192357	0.008137247	0.018350323	0.034508571	22.36673513
6	GATES_M	6.638792854	3.535309061	0.069633938	165.3264549	0.046972494	0.043797005	0.049013879	7.884491839
7	GATES_WELL#1	4.699156985	1.968276642	0.040007384	187.0419127	0.062930658	0.049131075	0.037042185	5.49326023
8	GATES_WELL#2	21.06944815	14.16604524	0.257051238	42.88792966	0.107254863	0.039658039	0.02081249	21.1958678
9	GATES_WELL#3	3.263452578	1.417550521	0.026106402	136.0118469	0.033572629	0.031134677	0.020519429	6.358991219
10	HARKERS_M	30.63439528	8.928552903	0.331728358	71.78341128	0.042332875	0.013448289	0.032194034	25.87041494
11	HARKERS_WELL#1	47.54934625	16.19855555	0.554604231	27.23606759	0.023198917	0.013417371	0.03207737	23.64456333
12	HARKERS_WELL#2	47.14563184	16.80364547	0.586590861	27.87286116	0.069312279	0.012880637	0.029500444	24.63763054
KDH_RO	13	1.48354	1.02344	0.03029	48.73307	0.00717	0.01042	0.02063	0.27167

Lab ID	Sample ID	IC (mg/L)				
		F	Cl	Br	NO3	SO4
NH-01	NH_WELL#1	0.706705363	1433.552262	10.6297283	ND	106.8033213
NH-07	NH_07_WELL#7	0.630078646	197.3927469	0.791902306	6.244197067	8.795451858
NH-08	NH_WELL#8	0.901877676	1464.669507	6.400264635	ND	111.3207177
NH-M	NH_MONITOR	0.714031542	14.88375501	0.038980699	4.883921492	39.9958859
CR-F-01	CRAVEN_FIRST_WELL#1	0.382881549	9.168516722	0.054413279	0.785266775	0.388380743
CR-F-02	CRAVEN_FIRST_WELL#2	0.25769009	11.83147209	0.047466795	0.693814184	0.148416637
CR-F-M	CRAVEN_FIRST_MONITOR	0.378298058	14.23831924	0.061457186	1.851586323	0.474817368
SKY-13	SKYCO_WELL#13	0.327729408	152.892235	0.564102039	0.529132639	ND
SKY-04	SKYCO_WELL#4	0.294860807	177.730815	0.842977281	0.797532162	ND
KDH-03	KDH_WELL#3	ND	81218.53681	710.2501539	ND	3740.407393
KDH-M	KDH_MONITOR	2.756759296	424.4090058	0.567595158	ND	8.381623341
KDH-M02		2.230982441	422.9750952	1.246563524	ND	10.95439455
MA-08	MARTIN_WELL#8	6.280421479	227.8374672	0.958730419	ND	58.76590215
MA-04	MARTIN_WELL#4	2.411539933	15.72748862	0.077226804	0.09464597	9.665809195
MA-M	MARTIN_MONITOR	7.95607093	623.2175731	3.380988573	ND	99.31984475
CR-CO-05	CRAVEN_CO_WELL#5	1.667616996	45.76473897	0.104523509	0.155107245	7.55847418
CR-CO-02	CRAVEN_CO_WELL#2	0.937938879	23.33188537	0.066191863	0.17103223	3.290964307
CR-CO-M	CRAVEN_CO_MONITOR	0.983294972	49.57315844	0.052115261	0.053090702	4.377624365
ON-06	ONSLOW_WELL#6	0.755074547	6.022284913	0.068366156	0.122193263	0.240055323
ON-M	ONSLOW_MONITOR	3.836427222	242.3742682	0.715168825	1.154834647	9.756371295
ON-02	ONSLOW_WELL#2	0.724725149	8.866584158	0.068879813	0.107301906	1.822747767
ON-D7	ONSLOW_WELL#D7	0.151672888	9.958618952	0.06038227	0.035351923	0.055118855
ON-D5	ONSLOW_WELL#D5	0.184804074	9.183312054	0.059174186	0.016430298	ND
1	CARTERET_M	0.632148623	16.74733389	0.077291845	0.239440269	0.014800566
2	CARTERET_WELL#2	0.349440545	8.544886337	0.026481491	0.365271871	0.082035054
3	CARTERET_WELL#3	0.348415398	9.436951209	0.032438675	0.118941808	0.047156222
4	CARTERET_WELL#4	0.351982685	11.02979444	0.093340147	0.484164377	0.032217406
5	CARTERET_WELL#5	0.397699481	8.691674929	0.082548001	0.38790565	0.061561221
6	GATES_M	2.283676301	40.71965318	0.116462428	ND	6.223988439
7	GATES_WELL#1	2.682733051	41.30962861	0.200252502	ND	9.313367512
8	GATES_WELL#2	0.513376303	2.870504552	0.039458535	0.054203566	0.039250858
9	GATES_WELL#3	3.707525461	13.77273065	0.060200205	ND	3.384327713
10	HARKERS_M	0.330927245	24.04226029	0.050634988	ND	0.219818242
11	HARKERS_WELL#1	0.334405131	10.26073466	0.04303526	0.298424832	0.190719101
12	HARKERS_WELL#2	0.364099618	7.548561103	0.049468783	0.405128229	0.137387235
KDH_RO	13	ND	73.2818284	0.431898116	0.03902611	0.809654374
KDH_3R	14	ND	2712.268661	12.42388149	1.687149466	149.0578605

Lab ID	Sample ID	ICYMS (mg/L)																									
		Li	Be	B	Mg	Al	Ca	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Mo	Ag	Cd	Sb	Ba	Tl	Pb	Th	U
NH-01	NH_WELL#1	11.3243	ND	196.388	20.2646	24.7347	82.5463	2.662075	3.5761	1.49004	152.6791	ND	ND	0.295008	1.75805	0.295008	2.662075	3.576101	429.7251	ND	ND	ND	ND	0.894025	ND	ND	ND	ND
NH-07	NH_07_WELL#7	7.20866	ND	121.614	10.3654	1.22161	51.6824	0.733064	ND	0.73306	54.06032	ND	ND	0.122161	3.909783	ND	0.855265	3.054516	303.8634	ND	ND	ND	ND	0.244361	ND	ND	ND	ND
NH-08	NH_WELL#8	10.6537	ND	161.327	23.4381	3.04391	67.3803	2.739523	0.91317	1.82635	169.2416	ND	ND	0.913174	35.30941	0.304391	2.435131	3.652697	472.4155	ND	ND	ND	ND	0.608783	ND	0.30439	ND	ND
NH-M	NH_MONITOR	3	0.6	ND	23.1	2.2	59.2	5.2	0.7	1	0.6	11.6	11.6	0.6	10.9	10.4	0.1	0.3	2.9	50.4	0.3	ND	ND	0.2	24.3	ND	0.1	ND
CR-F-01	CRAVEN_FIRST_WELL#1	0.70859	ND	27.2606	2.59617	69.9144	9.65409	0.62869	1.15099	0.70859	13.93564	0.116099	0.139473	12.87275	12.28226	0.116099	0.354296	3.42486	59.5317	0.354296	ND	ND	0.336197	25.69796	ND	0.1161	ND	ND
CR-F-02	CRAVEN_FIRST_WELL#2	9.8933	ND	52.6511	10.1537	1.5621	66.2591	0.26035	0.39053	36.9697	446.8909	ND	ND	0.390525	2.343151	ND	0.26035	3.254376	415.1252	ND	ND	ND	ND	0.5207	ND	0.26035	ND	ND
CR-F-M	CRAVEN_FIRST_MONITOR	5.26346	ND	54.5654	3.72435	1.97656	9.77649	0.232774	0.23277	5.58657	15.13026	ND	ND	47.03026	255.6151	ND	0.34916	2.560509	55.19339	ND	ND	ND	ND	1.396641	ND	1.97656	ND	ND
SKY-13	SKYCO_WELL#13	5.46129	ND	184.319	7.88853	3.18575	59.6191	0.910215	0.60681	69.6315	260.4732	ND	ND	0.455108	5.612994	ND	0.60681	2.42724	407.3213	ND	ND	ND	ND	5.157886	ND	ND	ND	ND
SKY-04	SKYCO_WELL#4	3.82607	ND	388.186	7.49272	2.23187	34.9129	0.956517	0.31864	76.6508	125.762	ND	ND	0.478255	1.913034	ND	1.115932	2.869551	270.3754	0.159419	ND	ND	ND	6.21736	ND	ND	ND	ND
KDH-03	KDH_WELL#3	117.359	ND	1352.03	134.675	5.75511	70.0649	31.52916	12.2613	31.5292	140.1297	ND	ND	1.751621	10.50973	49.0454	29.77756	15.76459	3596.079	1.751621	ND	ND	ND	1.751621	ND	1.75162	ND	ND
KDH-M	KDH_MONITOR	7.2471	ND	796.706	4.56552	9.92537	11.6554	1.575456	0.31509	2.99337	17.17247	ND	ND	101.4594	179.4444	0.315091	1.575456	1.260365	152.3466	ND	ND	ND	ND	0.630182	ND	ND	ND	ND
MA-05	MARTIN_WELL#5	5.16652	ND	2666.57	0.95652	3.25316	0.95652	0.191304	ND	2.29537	2.48773	ND	ND	0.382726	2.870457	ND	0.191304	3.253165	15.3091	4.401356	ND	ND	ND	49.56323	ND	ND	ND	ND
MA-04	MARTIN_WELL#4	4.65923	ND	2406.41	0.86252	2.93359	0.86252	0.172504	ND	2.07077	2.243332	ND	ND	0.345125	2.58846	ND	0.172504	2.933558	13.80512	3.968972	ND	ND	ND	44.69406	ND	ND	ND	ND
MA-M	MARTIN_MONITOR	5.14452	ND	1791.83	1.0289	22.6359	1.80058	1.286129	0.77166	2.05751	ND	ND	ND	261.0642	5.916194	0.257226	2.057806	3.343935	17.49135	6.946097	ND	ND	ND	83.53477	ND	0.51445	ND	ND
CR-CO-05	CRAVEN_CO_WELL#5	5.15309	ND	1873.33	1.28827	44.7214	1.84039	1.472311	0.36808	2.57654	20.79639	0.184039	0.338703	1.65835	4.78501	ND	0.920194	2.760583	27.05371	1.472311	ND	ND	ND	21.53255	ND	0.18404	ND	ND
CR-CO-02	CRAVEN_CO_WELL#2	3.41256	ND	1149.38	0.3825	5.5126	0.76751	0.393757	ND	4.06883	ND	ND	ND	3.281312	2.625049	ND	0.393757	1.57503	11.55022	0.787515	ND	ND	ND	12.20648	ND	ND	ND	ND
CR-CO-M	CRAVEN_CO_MONITOR	4.36011	ND	1324.3	0.83645	5.36629	1.17366	0.50309	ND	2.34775	ND	ND	ND	1.844662	2.160055	ND	0.167697	2.012359	21.46516	0.670788	ND	ND	ND	15.93117	ND	0.33539	ND	ND
ON-06	ONSLOW_WELL#6	5.12393	ND	1116.56	0.56933	1.85031	1.85031	0.284663	ND	0.28466	ND	ND	ND	0.853998	7.685992	ND	ND	1.850307	15.65845	ND	ND	ND	ND	0.142331	ND	ND	ND	ND
ON-M	ONSLOW_MONITOR	5.25307	ND	1564.21	0.83374	13.7567	1.45905	0.625307	ND	1.66748	ND	ND	ND	94.00441	55.36194	ND	0.208436	2.084355	15.34232	0.208436	ND	ND	ND	ND	ND	0.20844	ND	ND
ON-02	ONSLOW_WELL#2	5.03446	ND	1205.17	0.69923	2.23754	1.53831	0.139846	ND	2.23754	ND	ND	ND	0.979923	2.237538	ND	0.139846	1.957846	15.66277	0.139846	ND	ND	ND	0.139846	ND	0.13985	ND	ND
ON-DT	ONSLOW_WELL#DT	15.2259	ND	25.1899	4.70211	1.11955	76.4653	0.111955	ND	152.819	1199.934	ND	ND	0.89564	10.07595	ND	ND	1.679325	388.3719	ND	ND	ND	ND	0.89564	ND	ND	ND	ND
ON-D5	ONSLOW_WELL#D5	17.8756	ND	25.3235	4.2561	0.85122	74.3754	0.106403	ND	47.7747	176.6282	0.106403	0.113215	0.42561	4.894515	ND	0.106403	2.340855	254.5146	ND	ND	ND	ND	0.106403	ND	ND	ND	ND
1	CARTERET_M	12.2292	0	140.313	7.53455	3.83079	19.6872	0.334559	0.21353	0.19958	35.89296	0.023964	0.326503	10.5817	7.615203	0	0.334573	3.067951	212.2755	0	0.001271	0.000194	0	0.728646	0	0.6401	0.019539	0.0006
2	CARTERET_WELL#2	12.3073	0	120.145	19.5251	2.25734	143.842	0.193564	0.03165	1.13154	169.9194	0.112702	1.457647	0.264122	2.874013	0	0.27676	4.714725	889.9806	0	0.002594	0	0	1.034276	0	0	0	0.0002
3	CARTERET_WELL#3	13.9596	0	144.202	26.5645	3.02546	134.626	0.160916	0	2.65272	176.6381	0.101697	1.293506	0.372292	4.307561	0	0.251559	5.58407	849.431	0	0.003626	0	0	3.066597	0	0.02304	0	0.0035
4	CARTERET_WELL#4	14.4207	0	150.375	29.2611	2.1619	135.545	0.278726	0.16599	0.34263	155.3911	0.126401	1.279065	0.576086	2.477165	0.004426	0.227399	6.319058	806.2534	0.056356	0.005457	0.0077	0	3.388642	0.00042	0.01845	0.013083	0.0141
5	CARTERET_WELL#5	13.7626	0	165.675	25.3781	2.56874	136.508	0.387551	0.27744	0.47434	167.3625	0.121596	1.442263	2.930107	5.069705	0	0.231917	6.109611	894.9274	0.066545	0.003674	0.009905	0	5.504514	0	0.01666	0.002756	0.0126
6	GATES_M	5.65059	0	3666.33	2.90066	6.66516	3.97999	0.423053	0.23251	0.24042	9.000548	0.008769	0	114.4515	7.773537	0.184461	0.643451	4.135125	62.26166	6.092211	0.011091	0.01617	0	29.73783	0	0.09323	0.01729	0.0366
7	GATES_WELL#1	5.92766	0	4711.46	0.92156	18.7537	1.60069	0.492049	1.64052	2.11606	9.080467	0.012359	0	0.976499	2.466121	0.137687	1.068963	3.656112	30.5954	7.326341	0.004695	0.005573	0	31.23904	0.00129	0.0724	0.02844	0.0383
8	GATES_WELL#2	25.5027	0	717.2	14.2507	2.19546	22.0069	0.109421	0.14235	2.30501	73.7655	0.021702	0.48483	0.618412	2.535984	0	0.086935	6.921369	296.1025	0.497175	0.001235	0.010244	0	34.76325	0	0.09579	0	0.0081
9	GATES_WELL#3	5.40037	0	3870.91	0.67219	3.71111	1.05573	0.08574	0.99535	1.23465	5.540433	0	0	0.621381	3.639395	0.271327	0.319575	3.315361	19.46127	6.613606	0.005227	0.022503	0	19.55178	0	0.12087	0.006466	0.0237
10	HARKERS_M	9.14523	0	139.704	5.65531	1.83502	30.612	0.273993	0.49259	0.54711	56.65536	0.045249	0.651631	5.296053	5.157226	0.005999	0.548369	3.193183	356.5707	0.002239	0.002475	0	0	0.552971	0	0.45247	0.000116	0.0033
11	HARKERS_WELL#1	14.9235	0	143.134	17.5909	1.33864	54.1626	0.150707	0.74537	3.92899	101.5565	0.067113	1.146476	0.250652	4.755423	0	0.317116	5.390275	679.1437	0	0.002216	0	0	0.655721	0	0.00852	0	0.0016
12	HARKERS_WELL#2	14.0869	0	150.521	17.3555	1.29516	50.9021	0.118345	0.75733	4.3026	110.9346	0.067351	0.961596	0.203399	5.4333	0	0.318445	5.144527	709.3714	0	0.001445	0	0	0.55119	0	0.02732	0	0.0002
KDH_RD	13	3.60334	0	1763.67	0.50321	5.11582	0.41826	0.85696	0.41555	0	0	0	0	0.15175	2.27011	14.10877	0.75296	0.40946	20.56956	0	0.00139	0	0	0	0	0.02936	0	0.0005

Lab ID	Sample ID	Conductivity (µS)	
		Field	Lab
NH-01	NH_WELL#1	1216	1216
NH-07	NH_07_WELL#7	588	588
NH-08	NH_WELL#8	1219	1218
NH-M	NH_MONITOR	227.5	227.5
CR-F-01	CRAVEN_FIRST_WELL#1	471.1	471.1
CR-F-02	CRAVEN_FIRST_WELL#2	520	520
CR-F-M	CRAVEN_FIRST_MONITOR	462.2	462.8
SKY-13	SKYCO_WELL#13	NA	613
SKY-04	SKYCO_WELL#4	NA	633
KDH-03	KDH_WELL#3	NA	7160
KDH-M	KDH_MONITOR	631	631
MA-08	MARTIN_WELL#8	767	767
MA-04	MARTIN_WELL#4	687	687
MA-M	MARTIN_MONITOR	1033	1033
CR-CO-05	CRAVEN_CO_WELL#5	732	732
CR-CO-02	CRAVEN_CO_WELL#2	525	525
CR-CO-M	CRAVEN_CO_MONITOR	664	664
ON-06	ONSLOW_WELL#6	573	573
ON-M	ONSLOW_MONITOR	839	839
ON-02	ONSLOW_WELL#2	561	561
ON-D7	ONSLOW_WELL#D7	448	448
ON-D5	ONSLOW_WELL#D5	427.9	427.9
1	CARTERET_M	612	607
2	CARTERET_WELL#2	560	568
3	CARTERET_WELL#3	596	591
4	CARTERET_WELL#4	599	595
5	CARTERET_WELL#5	600	616
6	GATES_M	829	818
7	GATES_WELL#1	934	921
8	GATES_WELL#2	409.5	408.5
9	GATES_WELL#3	678	676
10	HARKERS_M	469.4	466.6
11	HARKERS_WELL#1	473.3	467.3
12	HARKERS_WELL#2	461	459.6

Lab ID	Sample ID	County	Water Utility	Population Served	Disinfection Method	Pre-Disinfection Treatment	Primary Aquifer	Secondary Aquifer	Pump Depth (bgs)	Well Depth (bgs)
NH-01	NH_WELL#1	New Hanover	Wrightsville Beach Water System	5087	Chlorine Gas		Pee Dee		108	179
NH-07	NH_07_WELL#7	New Hanover	Wrightsville Beach Water System	5087	Chlorine Gas		Pee Dee		115	163
NH-08	NH_WELL#8	New Hanover	Wrightsville Beach Water System	5087	Chlorine Gas		Pee Dee		108	165
NH-M	NH_MONITOR	New Hanover	Wrightsville Beach Water System		NA				NA	NA
CR-F-01	CRAVEN_FIRST_WELL#1	Craven	First Craven Sanitary District	6350	Chlorine Gas		Castle Hayne			
CR-F-02	CRAVEN_FIRST_WELL#2	Craven	First Craven Sanitary District	6350	Chlorine Gas		Castle Hayne			130
CR-F-M	CRAVEN_FIRST_MONITOR	Craven	First Craven Sanitary District		NA				NA	NA
SKY-13	SKYCO_WELL#13	Dare	Dare County Water System	22766	Sodium Hypochlorite		Lower Principle		160-180	
SKY-04	SKYCO_WELL#4	Dare	Dare County Water System	22766	Sodium Hypochlorite		Lower Principle		160-180	
KDH-03	KDH_WELL#3	Dare	Dare County Water System	22766	Chlorine Gas	Reverse Osmosis	Yorktown		160-180	
KDH-M	KDH_MONITOR	Dare	Dare County Water System		NA				NA	NA
KDH-M02										
MA-08	MARTIN_WELL#8	Martin	Town of Williamston	7650	Chlorine Gas		Upper Cape Fear		290-300	450
MA-04	MARTIN_WELL#4	Martin	Town of Williamston	7650	Chlorine Gas		Black Creek	Upper Cape Fear		
MA-M	MARTIN_MONITOR	Martin	Town of Williamston		NA				NA	NA
CR-CO-05	CRAVEN_CO_WELL#5	Craven	Craven County Water System	31000	Sodium Hypochlorite		Black Creek	Pee Dee	Black Creek: 606-695 Pee Dee: 253-257	Black Creek: 715 Pee Dee: 285-290
CR-CO-02	CRAVEN_CO_WELL#2	Craven	Craven County Water System	31000	Sodium Hypochlorite		Black Creek	Pee Dee	535-780	800
CR-CO-M	CRAVEN_CO_MONITOR	Craven	Craven County Water System		NA				NA	NA
ON-06	ONSLOW_WELL#6	Onslow	Onslow Water and Sewer Authority	118820	Sodium Hypochlorite		Black Creek			
ON-M	ONSLOW_MONITOR	Onslow	Onslow Water and Sewer Authority		NA				NA	NA
ON-02	ONSLOW_WELL#2	Onslow	Onslow Water and Sewer Authority	118820	Sodium Hypochlorite		Black Creek			
ON-D7	ONSLOW_WELL#D7	Onslow	Onslow Water and Sewer Authority	118820	Chlorine Gas		Castle Hayne			
ON-D5	ONSLOW_WELL#D5	Onslow	Onslow Water and Sewer Authority	118820	Chlorine Gas		Castle Hayne			
1	CARTERET_M	Carteret	Town of Beaufort		NA				NA	NA
2	CARTERET_WELL#2	Carteret	Town of Beaufort	4539	Chlorine Gas		Castle Hayne			390
3	CARTERET_WELL#3	Carteret	Town of Beaufort	4539	Chlorine Gas		Castle Hayne			300
4	CARTERET_WELL#4	Carteret	Town of Beaufort	4539	Chlorine Gas		Castle Hayne			305
5	CARTERET_WELL#5	Carteret	Town of Beaufort	4539	Chlorine Gas		Castle Hayne			305
6	GATES_M	Gates	Gates County Water System		NA				NA	NA
7	GATES_WELL#1	Gates	Gates County Water System	11612	Chlorine Gas		Cape Fear		200	422
8	GATES_WELL#2	Gates	Gates County Water System	11612	Chlorine Gas		Cape Fear		150	402
9	GATES_WELL#3	Gates	Gates County Water System	11612	Chlorine Gas		Cape Fear		150	375
10	HARKERS_M	Carteret	Harker's Island Sanitary District		NA				NA	NA
11	HARKERS_WELL#1	Carteret	Harker's Island Sanitary District	2229	Chlorine Gas		Yorktown			
12	HARKERS_WELL#2	Carteret	Harker's Island Sanitary District	2229	Chlorine Gas		Yorktown			
KDH_RO	13	Dare	Dare County Water System	22766		NA				
KDH_3R	14	Dare	Dare County Water System	22766		Reverse Osmosis				

Appendix B. Raw data tables of previously collected samples within Dare County Water System.

Lab ID	Sample ID	ICMPS (ppb)
		I
OBX 1	RB-22D	19.4
OBX 2	RB-21L	15.1
OBX 3	RB-20	19.4
OBX 4	RB-19D	15.3
OBX 5	RB-17D	25.9
OBX 6	RB-15D	23.6
OBX 7	RB-14L	19.3
OBX 8	RB-13D	22.0
OBX 9	RB-12D	24.0
OBX 10	RB-11L	19.8
OBX 11	RB-10L	15.1
OBX 12	Rb-9L	13.5
OBX 13	RB-8L	16.9
OBX 14	RB-7L	11.2
OBX 15	RB-6L	16.8
OBX 16	RB-5L	12.9
OBX 17	RB-3D	14.3
OBX 18	RO Well 3	147.7
OBX 19	RO Well 4	97.1
OBX 20	Anix-in	19.6
OBX 21	Anix-out	16.9
OBX 22	Filter-out	19.1
OBX 23	RO perm A-train	1.6
OBX 24	Skyco Pilot Interstage	16.9
OBX 25	Skyco Pilot raw	13.5
OBX 26	Skyco Pilot Stage 1	13.6
OBX 27	Skyco Pilot Stage 2	0.0
OBX 28	Well 14	15.1
OBX 29	Well 13	11.8
OBX 30	Well 8	14.0
OBX 31	Well 7	13.4
OBX 32	Well 5	12.5
OBX 33	Well 2	10.7
OBX 34	Well 4	12.3
OBX 35	Well 6	13.0
OBX 36	Well 10	15.2
OBX 37	Well 11	16.5

Lab ID	Sample ID	Alkalinity (mg/L)
		HCO3-
OBX 1	RB-22D	360
OBX 2	RB-21L	303
OBX 3	RB-20	372
OBX 4	RB-19D	277
OBX 5	RB-17D	456
OBX 6	RB-15D	409
OBX 7	RB-14L	317
OBX 8	RB-13D	373
OBX 9	RB-12D	376
OBX 10	RB-11L	368
OBX 11	RB-10L	332
OBX 12	Rb-9L	329
OBX 13	RB-8L	319
OBX 14	RB-7L	337
OBX 15	RB-6L	356
OBX 16	RB-5L	340
OBX 17	RB-3D	334
OBX 18	RO Well 3	259
OBX 19	RO Well 4	268
OBX 20	Anix-in	385
OBX 21	Anix-out	389
OBX 22	Filter-out	392
OBX 23	RO perm A-train	7
OBX 24	Skyco Pilot Interstage	427
OBX 25	Skyco Pilot raw	296
OBX 26	Skyco Pilot Stage 1	235
OBX 27	Skyco Pilot Stage 2	13
OBX 28	Well 14	256
OBX 29	Well 13	319
OBX 30	Well 8	302
OBX 31	Well 7	294
OBX 32	Well 5	304
OBX 33	Well 2	303
OBX 34	Well 4	327
OBX 35	Well 6	304
OBX 36	Well 10	254
OBX 37	Well 11	262

Lab ID	Sample ID	IC (mg/L)				
		F	Cl	Br	NO3	SO4
OBX 1	RB-22D	0.4988	35.1503	0.1402	0.1201	ND
OBX 2	RB-21L	0.2724	18.7194	0.0950	0.1010	ND
OBX 3	RB-20	0.3626	55.6372	0.1832	0.0136	0.0760
OBX 4	RB-19D	0.2739	30.1470	0.0834	0.0472	0.0564
OBX 5	RB-17D	0.2730	55.1074	0.1347	0.0674	ND
OBX 6	RB-15D	0.2487	39.3335	0.1447	0.1062	ND
OBX 7	RB-14L	0.0616	54.3251	0.1494	0.0022	ND
OBX 8	RB-13D	0.3505	64.6811	0.1781	ND	ND
OBX 9	RB-12D	0.3986	66.7729	0.1769	0.0098	0.2768
OBX 10	RB-11L	0.3439	57.3783	0.1616	0.0472	ND
OBX 11	RB-10L	0.1424	53.3142	0.1331	0.0874	ND
OBX 12	Rb-9L	0.1935	49.2900	0.1097	0.3059	2.7705
OBX 13	RB-8L	0.1759	33.7430	0.0945	0.1343	ND
OBX 14	RB-7L	0.2890	38.5702	0.1154	0.1621	ND
OBX 15	RB-6L	0.3581	51.6644	0.1445	0.0686	1.3391
OBX 16	RB-5L	0.2237	38.6972	0.1031	0.0873	ND
OBX 17	RB-3D	0.1433	54.2529	0.1220	0.1035	2.6869
OBX 18	RO Well 3	0.2264	8707.1813	25.6447	0.4661	643.9876
OBX 19	RO Well 4	ND	5295.1357	15.8099	1.4287	230.4383
OBX 20	Anix-in	0.3625	64.1455	0.1761	0.1290	0.1115
OBX 21	Anix-out	0.3667	63.3116	0.1633	0.0840	0.1385
OBX 22	Filter-out	0.3758	74.3535	0.0079	0.0958	0.2347
OBX 23	RO perm A-train	ND	99.6516	0.3890	0.0544	0.3173
OBX 24	Skyco Pilot Interstage	0.2022	73.7278	0.2258	0.8115	3.9979
OBX 25	Skyco Pilot raw	0.1017	71.5627	0.2356	0.2665	0.6177
OBX 26	Skyco Pilot Stage 1	0.0658	71.4748	0.2454	0.3010	ND
OBX 27	Skyco Pilot Stage 2	0.0016	4.2754	0.0191	0.1440	0.0255
OBX 28	Well 14	0.1202	67.3230	0.2088	0.2240	ND
OBX 29	Well 13	0.1209	45.6278	0.1497	0.0878	ND
OBX 30	Well 8	0.1234	124.9723	0.3728	0.1743	ND
OBX 31	Well 7	0.1126	106.0498	0.3269	0.0535	ND
OBX 32	Well 5	0.0612	82.0841	0.2542	0.0191	0.0855
OBX 33	Well 2	0.0451	69.1466	0.2161	0.2304	ND
OBX 34	Well 4	0.0842	57.8886	0.2028	0.1132	ND
OBX 35	Well 6	0.1077	50.7538	0.1548	0.1528	ND
OBX 36	Well 10	0.1021	141.3365	0.4465	0.1068	ND
OBX 37	Well 11	ND	116.7869	0.3482	0.0877	7.2679

Lab ID	Sample ID	DCP (mg/L)							
		Ca	Mg	Sr	Na	Fe	Ba	Mn	Si
OBX 1	RB-22D	50.8629	13.8026	0.5391	87.5487	0.9590	0.0067	0.0652	12.5481
OBX 2	RB-21L	67.1874	11.9010	0.5895	20.4841	2.1520	0.0028	0.0726	10.4675
OBX 3	RB-20	72.0240	22.3050	0.7732	49.8297	0.2709	0.0030	0.0509	12.2901
OBX 6	RB-15D	105.1422	6.9808	1.0474	27.6029	5.3549	0.0033	0.1348	8.6099
OBX 7	RB-14L	85.7531	3.9661	0.5034	30.3287	2.2189	0.0030	0.0893	3.8980
OBX 8	RB-13D	76.4880	19.6815	0.8288	44.3398	0.3690	0.0030	0.0544	9.9696
OBX 9	RB-12D	70.6954	22.9852	0.7947	54.7274	0.3278	0.0036	0.0563	11.6489
OBX 10	RB-11L	69.4903	20.7739	0.6909	39.9326	0.1712	0.0029	0.0349	12.2328
OBX 11	RB-10L	85.3149	6.1011	0.6472	28.0139	0.3515	0.0040	0.3637	7.5115
OBX 12	Rb-9L	74.9508	11.1744	0.5548	27.3210	0.6146	0.0036	0.1070	8.6661
OBX 13	RB-8L	81.7282	7.8348	0.6038	23.3408	3.4964	0.0012	0.1260	9.8199
OBX 14	RB-7L	67.9481	18.5193	0.7697	27.1607	1.2960	0.0011	0.0524	10.1159
OBX 15	RB-6L	54.9586	30.2056	0.5358	32.3523	0.6993	0.0010	0.0543	12.6706
OBX 16	RB-5L	80.7956	9.1089	0.6168	26.4293	1.3816	0.0012	0.1371	8.1477
OBX 17	RB-3D	85.2682	8.3378	0.6021	27.5271	0.8269	0.0012	0.1566	8.5091
OBX 18	RO Well 3	441.5033	596.0980	13.6456	5135.3150	0.1067	0.1868	0.1417	10.3746
OBX 19	RO Well 4	301.2102	346.9189	8.8727	3023.4774	0.0000	0.1845	0.1488	11.2481
OBX 20	Anix-in	69.6188	24.4006	0.7393	47.2628	0.2870	0.0022	0.0449	11.9801
OBX 21	Anix-out	68.7646	24.5773	0.7326	48.1253	0.3372	0.0013	0.0454	11.6452
OBX 22	Filter-out	71.4368	24.8699	0.6930	47.2667	0.0210	0.0036	0.0126	11.6282
OBX 23	RO perm A-train	0.7656	0.6093	0.0178	68.9223	0.0000	0.0000	0.0023	0.2170
OBX 24	Skyco Pilot Interstage	75.0890	14.3427	0.5175	118.0012	0.5449	0.0126	0.1176	13.5497
OBX 25	Skyco Pilot raw	53.5932	8.4734	0.3443	83.4127	0.3485	0.0122	0.0799	11.9302
OBX 26	Skyco Pilot Stage 1	41.6314	6.0962	0.2730	72.1050	0.2476	0.0108	0.0558	11.1210
OBX 27	Skyco Pilot Stage 2	0.7115	0.1497	0.0046	6.9377	0.0033	0.0000	0.0042	1.1253
OBX 28	Well 14	55.7272	7.5631	0.3404	53.4659	0.3735	0.0097	0.0767	10.3404
OBX 29	Well 13	54.2166	7.4661	0.3239	62.0719	0.3237	0.0091	0.0649	11.8915
OBX 30	Well 8	59.3659	16.5430	0.3993	86.9804	0.2613	0.0142	0.0725	16.9340
OBX 31	Well 7	53.2620	16.0205	0.3650	77.9096	0.3637	0.0147	0.0835	17.0383
OBX 32	Well 5	49.4494	10.1183	0.3305	90.8616	0.1857	0.0126	0.0666	12.7729
OBX 33	Well 2	43.0559	6.5926	0.2841	93.3765	0.1757	0.0111	0.0736	9.9953
OBX 34	Well 4	39.3286	8.8415	0.2785	113.3269	0.1693	0.0097	0.0806	12.2033
OBX 35	Well 6	61.0801	8.9689	0.3481	41.4160	0.5054	0.0057	0.0836	13.9680
OBX 36	Well 10	72.5388	10.1860	0.4441	55.7533	0.4804	0.0085	0.0821	10.6239
OBX 37	Well 11	70.7219	10.3537	0.4323	57.1971	0.8410	0.0085	0.0688	12.1456

Lab ID	Sample ID	ICPMS (mg/L)																										
		Li	Be	B	Mg	Al	Ca	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Mo	Ag	Cd	Sb	Ba	Tl	Pb	Th	U
OBX 1	RB-22D	13.6169	0.0000	272.9811	13.0689	3.8763	50.2277	1.4167	0.9739	64.1782	457.5673	0.1793	5.2735	1.4887	70.0689	0.2192	0.0000	3.6146	666.8657	0.5198	0.0504	0.0274	0.0134	6.3993	0.0000	0.3159	0.5406	0.0192
OBX 2	RB-21L	12.0398	0.0000	84.4028	11.4806	4.3844	77.8115	3.4494	1.0439	63.8970	1005.0286	0.1642	4.0543	0.1431	13.3031	0.0133	0.0000	2.5830	767.5411	0.3148	0.0099	0.0000	0.0000	3.2413	0.0014	0.1997	0.2799	0.0000
OBX 3	RB-20	15.2468	0.0000	144.5226	23.3217	4.8778	77.8856	3.1556	1.6973	36.4668	233.7964	0.1919	2.1212	2.1368	26.0123	0.1969	0.0000	3.7547	987.6451	0.3046	0.0202	0.0000	0.0118	3.7921	0.0000	0.7215	0.0323	0.0000
OBX 4	RB-19D	9.8999	0.0000	131.2884	11.2739	5.2528	62.6826	2.3467	0.9551	56.6410	493.1805	0.1125	1.3689	0.8425	16.2224	0.0796	0.0000	2.9773	542.1501	0.2229	0.0000	0.0000	0.0000	3.4043	0.0000	0.1271	0.0000	0.0000
OBX 5	RB-17D	13.7546	0.0000	151.3603	44.0650	2.8103	68.8728	1.8888	1.2748	29.9476	784.0133	0.2141	4.2309	0.5225	1214.5436	0.0398	0.0000	4.8108	859.2232	0.1691	0.0000	0.0000	0.0000	2.6665	0.0000	1.5740	0.0000	0.0000
OBX 6	RB-15D	13.8519	0.0000	52.8492	6.1968	6.0290	127.8004	4.4507	1.5260	120.8725	2410.0189	0.2689	3.2564	5.4595	1263.7347	0.1227	0.0000	2.4359	1399.2472	0.0000	0.0000	0.0000	0.0000	3.6663	0.0000	0.7662	0.0000	0.0000
OBX 7	RB-14L	3.5421	0.0000	24.5359	3.6382	16.8513	105.1726	6.5041	1.9036	86.8837	1133.5589	0.1736	7.0180	0.2462	18.5363	0.1637	0.0000	1.4578	655.2159	0.0040	0.0000	0.0000	0.0000	2.3334	0.0000	0.0633	0.0000	0.0000
OBX 8	RB-13D	13.8200	0.0000	111.8789	19.7770	6.6564	84.7170	5.9639	1.8123	47.2743	290.4746	0.1634	1.5036	0.4868	12.6578	0.0617	0.0000	3.1740	1095.9173	0.0000	0.0000	0.0000	0.0000	2.9331	0.0000	0.0539	0.0000	0.0000
OBX 9	RB-12D	13.1628	0.0000	155.3656	23.8866	4.6136	75.8083	4.0635	1.6226	43.1354	264.8788	0.1709	1.5315	0.3959	8.9870	0.1019	0.0000	3.7556	1023.5919	0.0513	0.0000	0.0000	0.0000	2.7590	0.0000	0.0680	0.0000	0.0000
OBX 10	RB-11L	16.2099	0.0549	131.8541	21.8504	2.6421	75.4475	2.4119	1.5247	27.9046	196.8875	0.1612	1.4284	0.4572	12.8883	0.2349	1.1718	3.4778	907.7586	0.0175	0.0000	0.0000	0.0174	2.2573	0.0000	0.1023	0.0000	0.0000
OBX 11	RB-10L	21.2009	0.1385	38.0088	5.7376	6.5939	105.9900	4.3849	2.4538	381.2188	332.8491	0.2197	3.4643	0.5736	16.1651	0.2900	0.3924	1.7987	903.9758	0.1270	0.0021	0.0307	0.0579	3.4019	0.0000	0.1180	0.0000	0.0055
OBX 12	Rb-9L	14.5919	0.0488	75.3685	10.2513	4.3850	88.3929	2.2342	1.4469	105.0549	400.1397	0.1381	1.6897	0.6759	12.4235	0.2123	0.6386	1.9053	753.0636	0.1018	0.0060	0.0079	0.0292	2.4768	0.0000	0.0353	0.0000	0.0070
OBX 13	RB-8L	13.2709	0.1271	47.7633	6.6628	4.2254	91.7786	4.1613	1.3954	106.5220	1538.9947	0.2119	10.4213	0.3519	8.3277	0.3673	0.0000	1.8224	748.7968	0.1124	0.0050	0.0312	0.0083	1.6927	0.0000	0.2110	0.0000	0.0097
OBX 14	RB-7L	14.4196	0.0166	78.3996	18.4995	2.6682	75.0549	1.9122	1.5011	41.2408	640.7537	0.1426	2.4693	0.3445	11.2285	0.1305	0.0771	2.8409	1016.2817	0.0314	0.0053	0.0046	0.0076	2.7001	0.0000	0.5267	0.0000	0.0000
OBX 15	RB-6L	11.6793	0.0802	142.1981	32.1318	1.6239	55.3682	1.0546	1.4049	42.6671	367.0819	0.1181	1.6283	0.8064	4.7027	0.1513	0.6123	3.8843	657.0724	0.1590	0.0000	0.0000	0.0446	1.9318	0.0000	0.1942	0.0000	0.0000
OBX 16	RB-5L	12.1605	0.0975	90.8389	8.4167	2.9599	97.0430	2.8909	1.3130	128.5704	742.4649	0.1998	6.9586	0.3634	10.6620	0.3263	0.7738	1.7690	810.7131	0.1095	0.0052	0.0092	0.0396	2.0559	0.0000	0.2399	0.0000	0.0000
OBX 17	RB-3D	17.0445	0.1448	58.6680	7.8704	5.2067	108.2635	2.8875	1.6387	151.7071	550.0123	0.2014	2.0854	1.0882	47.2855	0.2623	0.6125	1.7589	827.1147	0.1578	0.0033	0.0289	0.0372	2.5646	0.0000	0.0187	0.0000	0.0357
OBX 18	RO Well 3	130.1866	0.0000	1787.1689	552.0517	35.5287	388.1486	46.1555	140.6293	36.4357	782.0848	1.4239	9.8067	6.4303	53.5299	16.4887	106.6342	37.0345	14202.0139	0.0000	0.0000	0.0000	0.4071	224.5143	0.0000	0.0000	0.0000	0.0000
OBX 19	RO Well 4	95.8249	1.1150	1732.7944	337.6751	77.0978	277.9092	29.7397	99.6642	23.9294	354.1264	1.0280	5.2528	5.5942	43.8969	10.4845	57.0086	26.4798	9951.0573	0.0000	0.1117	0.0000	0.0000	185.6729	0.0000	0.0000	0.0000	0.0000
OBX 20	Anbr-in	15.0655	0.0925	150.5658	25.8498	10.2330	76.9537	2.9623	1.6613	36.2370	253.2840	0.1908	1.5630	0.6469	9.6969	0.2349	0.9541	4.0059	966.3717	0.0402	0.0031	0.0164	0.0015	3.0141	0.0007	0.1086	0.0000	0.0000
OBX 21	Anbr-out	15.4626	0.0202	147.6947	27.6827	3.9767	79.6359	0.5942	1.4726	39.0330	282.4848	0.1673	1.4728	0.8280	6.5302	0.1979	0.7690	3.9664	974.9283	0.0892	0.0000	0.0000	0.0187	2.2742	0.0000	0.0000	0.0000	0.0000
OBX 22	Filter-out	14.9025	0.0473	139.9279	25.9272	1.0605	77.2494	0.5945	1.7381	1.7375	127.3230	0.1401	1.4920	23.9761	12.8284	0.2492	1.3402	3.8484	950.4660	0.0699	0.0128	0.0000	0.0154	2.0176	0.0157	4.4443	0.0000	0.0000
OBX 23	RO perm A-train	2.3424	0.2857	961.8394	0.5587	1.7247	0.8380	0.7386	2.3621	0.3918	0.0000	0.0457	0.4050	0.5908	4.7502	0.3985	1.9977	0.6430	18.5932	0.1026	0.0495	0.0931	0.0609	0.4819	0.0270	0.1391	0.0000	0.0219
OBX 24	Skyco Pilot Interstage	5.0837	0.0000	254.4864	12.7946	4.6817	78.5456	1.1398	1.5385	104.3419	358.4271	0.1384	1.2026	1.7522	5.9542	0.1735	1.2834	3.1008	579.9438	0.4740	0.0000	0.0000	0.0000	12.9556	0.0000	0.0000	0.0000	0.0000
OBX 25	Skyco Pilotraw	4.3047	0.5098	244.3223	8.0191	19.7972	53.9422	0.6953	3.2146	70.0147	224.2081	0.1578	5.0946	0.9457	47.1786	0.5288	3.5732	2.4994	380.3753	0.2623	0.0504	0.3604	0.1379	8.4790	0.0541	0.0573	0.0000	0.0260
OBX 26	Skyco Pilot Stage 1	3.9603	0.3255	243.5838	5.7641	1.2680	42.1251	0.5462	2.2039	54.0743	166.7354	0.0878	0.6054	0.4693	6.4929	0.4554	4.1602	2.2183	290.1040	0.0543	0.0567	0.1324	0.1114	6.4012	0.0590	0.0218	0.0000	0.0317
OBX 27	Skyco Pilot Stage 2	0.5424	0.2793	242.1593	0.1424	1.7770	0.7817	0.1697	0.5784	0.9759	0.0000	0.0301	0.1952	0.3899	10.3145	0.3011	2.9959	0.2113	6.1064	0.0000	0.0352	0.0941	0.1248	0.0000	0.0368	0.0341	0.0000	0.0151
OBX 28	Well 14	4.3720	0.5357	152.3171	8.0588	2.0051	59.0279	0.7109	2.0901	75.4008	278.8278	0.1401	1.1668	0.6580	5.4920	0.4490	3.8421	2.3308	397.5786	0.2493	0.0704	0.1326	0.0754	6.4721	0.0582	0.0995	0.0000	0.0446
OBX 29	Well 13	15.5606	0.0000	199.2629	7.5236	11.6838	57.4217	0.5586	1.4359	65.1828	244.1086	0.0922	1.1237	0.3285	8.2419	0.1074	0.0000	2.2947	383.0505	0.0000	0.6874	0.0501	0.0000	6.0535	0.0000	0.2890	0.0000	0.0000
OBX 30	Well 8	7.5267	0.0000	260.7040	16.1373	1.7200	59.4130	0.9035	2.1519	75.1327	200.4662	0.0437	0.7914	0.2082	3.5075	0.0811	0.0000	3.4788	471.6547	0.0000	0.0000	0.0000	0.0000	11.2879	0.0000	0.0000	0.0000	0.0000
OBX 31	Well 7	5.9267	0.1476	264.9357	15.7870	2.0971	52.9051	0.9540	2.4965	84.4834	246.4124	0.0943	0.9533	1.5494	21.0708	0.3948	2.1020	3.3781	418.0301	0.0946	0.0146	0.0296	0.0028	12.3487	0.0323	0.0301	0.0000	0.0000
OBX 32	Well 5	4.3428	0.0992	260.1675	9.6501	0.9006	48.3477	0.7887	1.9290	61.1863	145.1679	0.0705	0.6680	0.2334	4.3174	0.2693	0.7814	2.5656	364.0853	0.0673	0.0224	0.0000	0.0000	10.0582	0.0064	0.0001	0.0000	0.0000
OBX 33	Well 2	3.2481	0.0000	286.6207	6.1394	1.3641	43.2389	0.7156	1.6546	75.1137	142.1261	0.0461	0.4499	0.7858	5.8445	0.1200	1.1068	2.3950	305.8529	0.0648	0.0019	0.0000	0.0000	8.0468	0.0081	0.0000	0.0000	0.0000
OBX 34	Well 4	3.6095	0.0000	393.0984	7.1418	1.6254	33.6025	0.6350	1.2635	74.9055	108.4500	0.0239	0.2247	0.1484	5.5373	0.0000	0.0000	2.7979	261.5547	0.0676	0.0000	0.0000	0.0000	6.2938	0.0000	0.0000	0.0000	0.0000
OBX 35	Well 6	6.1887	0.0000	121.3237	7.7796	1.7063	67.5936	0.5614	1.2276	82.6015	336.5706	0.0468	0.7044	0.3378	3.1394	0.0000	0.0000	2.3528	440.1996	0.0000	0.0000	0.0000	0.0000	4.8859	0.0000	0.0000	0.0000	0.0000
OBX 36	Well 10	4.9272	0.0000	108.0041	8.8076	1.7013	80.8066	1.0165	2.8897	77.3509	347.9685	0.0974	1.0676	0.1954	7.5934	0.0145	0.0000	2.5881	583.0136	0.0000	0.0003	0.0000	0.0000	6.8333	0.0000	0.1505	0.0000	0.0000
OBX 37	Well 11	3.9452	0.0000	103.7059	9.7216	0.9099	78.4175	1.0398	2.7103	65.3660	521.2981	0.0555	0.9372	0.2589	3.4650	0.0408	0.0000	2.2019	534.4444	0.0000	0.0000	0.0000	0.0000	8.0174	0.0000	0.0000	0.0000	0.0000

Appendix C: USGS Castle Hayne and Peedee Data, page 1 of 2

Station Name	Aquifer	Well Depth (fbls)	Sample Date	pH (standard units)	Specific Conductance (µS/cm at 25°C)	Temperature (°C)	Total Dissolved Solids (mg/L)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Alkalinity (mg/L as CaCO3)	Bicarbonate, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iron, dissolved (µg/L)
NH-833	CH	39	Aug. 31, 2012	6.9	1170	20.5	617	118	12.4	3.18	101	217	264.4	36.1	215	0.647	7.1
NH-818	CH	43	Sept. 5, 2012	7.1	1440	19.2	746	110	18.4	4.33	152	177	215.3	36.4	318	0.868	9.1
NH-842	CH	45	Aug. 27, 2012	7.2	21000	19.4	13100	307	468	117	3710	238	288.7	965	7350	24.1	47.4
NH-817	CH	47	Aug. 29, 2012	7	893	20.1	468	96.3	11	3.45	72.5	187	227.5	27.4	145	0.371	< 6.4
NH-840	CH	48	Aug. 29, 2012	7	1890	21.2	966	117	27.2	8.49	202	197	239.7	72.2	419	1.33	17.4
NH-841	CH	48	Aug. 27, 2012	6.9	5830	19.4	3350	243	91.4	16	845	207	252.1	205	1820	5.51	< 9.6
NH-815	CH	49	Aug. 29, 2012	7	590	19.7	315	94.1	7.03	2.52	22.8	207	252	19.1	45	0.085	5.3
NH-829	CH	50	Aug. 30, 2012	7	4440	19	2340	208	53.4	8.31	562	167	202.9	113	1290	4.39	< 9.6
NH-849	CH	52	Aug. 29, 2012	7	1470	19.5	781	107	21.4	5.43	154	197	239.7	47.8	326	0.945	5.1
NH-851	CH	53	Aug. 29, 2012	7.1	3550	20.6	1850	122	52.8	13.7	469	197	239.5	128	947	2.79	8.8
BR-297	CH	57	Aug. 29, 2012	7.1	17400	21.9	9880	186	276	160	2930	258	313.7	396	5760	16.7	136
NH-821	CH	60	Aug. 29, 2012	7.1	1310	21.7	688	94.6	19.2	5.42	142	187	227.2	38.4	275	0.805	3.8
NH-826	CH	60	Aug. 30, 2012	7	2050	19.8	1110	123	28.2	5.78	255	197	239.4	74.6	504	1.52	91.9
NH-831	CH	60	Aug. 28, 2012	7.2	1720	21.4	853	91	25.4	6.68	189	167	201.6	60	380	1.09	4.8
NH-870	CH	60	Aug. 29, 2012	6.8	1410	19.3	730	136	3.98	1.98	135	191	232.7	26.2	305	0.106	7890
NH-869	CH	65	Sept. 7, 2012	5	131	20.1	72	12.1	1.81	1.95	8.86	21	26.1	21.9	12.6	0.072	406
NH-830	CH	67	Aug. 29, 2012	7.1	398	18.9	214	77.9	2.37	0.9	7.32	177	215.1	4.5	13.6	0.034	869
NH-871	CH	70	Aug. 29, 2012	6.3	395	20	193	47.7	6.76	2.66	17.4	84	102.3	8.23	59.7	0.147	76.2
NH-989	CH	72.38	Sept. 5, 2012	7.1	316	20.6	168	62.5	1.55	0.64	4.99	151	183	0.96	6.85	0.038	276
PE-115	CH	73	Aug. 29, 2012	7.1	2210	19.5	1280	148	27.3	2.24	298	175	212.9	84.4	610	1.85	6000
BR-082	CH	74	Aug. 30, 2012	7.4	422	20.4	222	73.9	3.71	2.76	11.5	192	233.4	< 0.09	13.9	0.041	461
NH-820	CH	75	Aug. 30, 2012	7	448	19.4	236	80.9	2.93	1.27	13.2	197	240	< 0.09	17.8	0.045	1680
BR-111	CH	80	Aug. 28, 2012	7.2	438	17.9	241	82	2.11	1.28	11.3	217	264.8	< 0.09	10.6	0.032	3620
NH-548	CH	80	Sept. 5, 2012	6.8	523	19	285	106	2.39	0.86	9.04	252	306.5	1.7	11.3	0.014	3370
NH-857	CH	80	Aug. 30, 2012	6.8	473	18.3	243	86.1	2.32	1.08	9.87	192	233.8	1.1	22.7	0.077	4130
PE-116	CH	90	Aug. 30, 2012	6.9	413	18.7	226	78.9	2.28	0.91	9.08	196	238.6	1.74	15.4	0.043	481
PE-117	CH	90	Aug. 30, 2012	7.1	756	21.7	409	81.2	6.4	1.1	72.9	181	220.3	19.4	117	0.398	1800
NH-558	CH	95	Sept. 5, 2012	6.8	566	17.3	305	108	2.71	1.15	11.3	264	321.4	0.28	14	0.048	8850
NH-853	CH	98	Aug. 28, 2012	7.1	431	19.9	240	73.6	5.36	1.56	13.1	197	240.1	11.1	16.6	0.071	221
NH-556	CH	100	Sept. 5, 2012	6.8	542	17.3	287	99.4	3.25	1.12	10.5	248	301.6	< 0.09	12.6	0.038	11900
PE-112	CH	105	Aug. 30, 2012	7.4	283	19.6	155	46.3	2.65	0.88	7.76	66	79.7	42.1	15.6	0.087	294
BR-279	CH	118.9	Aug. 28, 2012	7.2	65	20.1	297	100	3.01	1.82	13.7	250	304.9	0.24	13.9	0.038	6040
NH-858	CH	140	Aug. 28, 2012	7.7	312	19.1	163	44.3	4.56	2.73	13.4	104	126.7	1.86	33.9	0.1	10.9
NH-860	CH	150	Aug. 29, 2012	7.5	410	19.8	217	31.9	11.5	8	33.1	130	158.5	1.61	52.1	0.217	< 3.2
NH-520	CH	174	Sept. 6, 2012	6.7	594	20.4	300	45.5	25.8	22.2	25.6	169	205.5	0.14	79.2	0.053	26.1
NH-890	CH	176	Sept. 6, 2012	6.7	459	20.5	228	33.1	26.2	16.2	14.4	163	198	0.3	40.4	0.038	131
BR-273	CH	--	Aug. 29, 2012	6.9	16900	20.3	9710	132	316	136	2900	427	520.5	518	5470	18.1	< 32
NH-823	CH	--	Sept. 6, 2012	6.9	1810	19.4	979	132	24.6	6.25	216	223	272	52.7	412	1.31	< 6.4
NH-825	CH	--	Aug. 31, 2012	6.9	1660	20.8	864	130	18.9	5.08	183	268	326	35.4	330	0.528	< 3.2
NH-837	CH	--	Aug. 29, 2012	7	1080	19.9	554	99.9	14	4.28	96.3	187	227.4	32.9	194	0.525	20
NH-879	CH	--	Sept. 5, 2012	7	1390	19	763	109	16.9	7.83	167	278	337.9	24.1	271	0.9	105

USGS Castle Hayne and Peedee Data, page 2 of 2

Station Name	Aquifer	Well Depth (fbls)	Sample Date	pH (standard units)	Specific Conductance (µS/cm at 25°C)	Temperature (°C)	Total Dissolved Solids (mg/L)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Alkalinity (mg/L as CaCO3)	Bicarbonate, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Iron, dissolved (µg/L)
NH-884	CH	--	Sept. 5, 2012	7	518	23	279	94.1	3.84	1.18	16.9	201	244.7	13.5	28.5	0.081	179
BR-146	PD	36	Aug. 27, 2012	6.1	106	18.4	51	5.81	0.568	0.96	6.33	38	46.3	0.14	6.77	0.026	7500
NH-864	PD	55	Aug. 31, 2012	5.6	201	19.3	107	26.7	2.57	1.59	8.45	50	60.5	19.4	18.6	0.046	339
NH-859	PD	65	Aug. 31, 2012	6.9	591	19.9	308	94.5	4.88	2.01	18.6	242	294.3	<0.09	34.8	0.048	8580
NH-862	PD	92	Sept. 7, 2012	7.1	567	22.7	335	111	2.21	1.95	12.1	207	252.1	69.5	13.9	0.103	57.2
NH-834	PD	95	Sept. 7, 2012	7.4	585	22.8	328	87	6.62	4.23	32.5	227	276.1	15.8	45.2	0.03	10.2
BR-372	PD	100	Aug. 27, 2012	7.4	1380	18.7	727	55.5	22.3	17.1	185	225	273.3	26.8	285	1.02	153
PE-110	PD	100	Aug. 29, 2012	7	737	18.1	409	94.3	9.6	6.5	55.3	288	350.9	3.71	66.9	0.301	3.9
NH-835	PD	140	Aug. 28, 2012	7.1	1660	21.2	884	123	20.5	8.8	194	258	313.4	28.3	353	1.31	30.9
NH-883	PD	147	Sept. 6, 2012	6.6	518	24.1	266	78.5	5.36	2.21	17.6	201	244.2	18	23.9	0.083	103
NH-827	PD	150	Sept. 6, 2012	7.1	571	19.4	320	86.5	10.4	4.4	25	268	325.7	1.05	32	0.076	11.1
NH-845	PD	150	Aug. 28, 2012	7.3	530	19.5	279	86.8	9.68	3.67	18.1	232	282.6	0.27	21.1	0.062	68.8
NH-892	PD	163	Sept. 6, 2012	7.4	671	20.1	349	49.8	12.6	8.18	65.1	165	199.9	11.5	102	0.326	18.8
NH-850	PD	165	Aug. 28, 2012	7	3420	19.8	1880	179	38.4	10.8	473	268	325.8	93.9	919	2.81	55.9
NH-876	PD	165	Aug. 27, 2012	7.2	609	18.9	340	84	11.1	4.61	35	272	331.1	1.1	40.8	0.147	16.8
NH-893	PD	165	Sept. 6, 2012	7.2	1160	20.3	601	80.6	19.2	7.53	124	195	236.5	21.3	231	0.715	68.7
NH-832	PD	167	Aug. 27, 2012	7.2	1970	20.5	1080	129	24.5	9.76	240	273	331.9	40.6	470	1.61	1640
NH-564	PD	170	Sept. 5, 2012	7.1	511	18.5	273	80.6	7.79	2.91	22.2	225	274.1	0.41	24.1	0.082	16.3
NH-865	PD	170	Aug. 28, 2012	7.2	1360	19.5	705	99.6	17	2.67	146	181	220.1	29.2	299	0.937	1620
NH-875	PD	170	Sept. 7, 2012	7.8	757	27.5	393	58.6	12.8	6.51	77	167	201.2	1.92	136	0.478	13.1
NH-822	PD	172	Sept. 4, 2012	7	2070	19.1	1100	134	24.3	8.53	257	270	328.5	40.3	476	1.63	19.2
NH-572	PD	175	Sept. 5, 2012	7	561	17.4	295	84.7	7.06	3.01	27.6	227	276.7	0.79	35.2	0.103	281
NH-574	PD	175	Sept. 5, 2012	7.7	519	18.3	277	96.2	4.54	2	14.3	227	276.9	3.98	19.5	0.059	398
NH-582	PD	175	Sept. 5, 2012	7	527	17.9	286	86.3	9.47	3.06	16.7	248	301.3	1.45	20.5	0.063	4.1
NH-824	PD	180	Aug. 29, 2012	7	1170	21.1	623	96.8	16.7	6.96	125	278	338.1	9.84	200	0.683	57.9
NH-866	PD	180	Aug. 28, 2012	7.4	912	19.9	480	48.8	15.5	8.18	109	179	217.8	13.7	176	0.738	18.5
NH-872	PD	180	Sept. 7, 2012	7.1	777	25.8	424	99.7	10	6.01	54.5	290	351.9	0.56	78.8	0.039	181
NH-891	PD	180	Sept. 6, 2012	7.4	1010	20.2	525	51.9	15.6	11	126	165	199.8	23.5	198	0.683	23.9
NH-843	PD	186	Aug. 30, 2012	6.9	830	19.6	441	106	8.35	5.48	64.3	268	326	<0.09	95.7	0.321	54
NH-828	PD	190	Aug. 28, 2012	7.2	1020	21.1	549	94	11.6	7.53	101	268	325.2	12.2	161	0.586	10.2
NH-836	PD	190	Aug. 30, 2012	6.9	967	24.6	523	106	9.17	5.83	89	268	326	4.74	148	0.503	84
BR-081	PD	200	Aug. 30, 2012	7.4	700	20.4	378	65.7	10	8.96	68.6	242	293.8	1.17	77.4	0.238	1160
NH-512	PD	200	Sept. 6, 2012	6.9	1030	19.2	544	101	22.9	21	73.1	272	330.9	6.04	157	0.502	503
NH-544	PD	202	Sept. 6, 2012	7.4	1040	20.5	532	45.8	16.6	12.9	131	130	158.3	15	232	0.925	21.1
NH-525	PD	220	Sept. 6, 2012	7.4	554	20.4	289	32.2	13.1	15.5	51.4	134	162.9	3.87	91.8	0.29	7.6
NH-844	PD	--	Sept. 7, 2012	7	640	18.2	350	88.2	6.65	4.05	39.9	213	259.4	21.9	58.8	0.196	2740
NH-846	PD	--	Aug. 31, 2012	6.9	1060	19.5	538	108	10.5	5.92	95.5	258	313.8	4.37	159	0.515	33.1
NH-847	PD	--	Sept. 7, 2012	6.9	462	24.6	251	68.9	4.25	1.78	24	165	200.7	14.4	37.9	0.131	570
NH-848	PD	--	Aug. 29, 2012	7	995	21.4	526	108	10.7	5.88	88	268	325.7	3.77	149	0.501	4.9
NH-861	PD	--	Aug. 28, 2012	6.9	707	19.4	385	81.5	27.9	23.6	18.1	298	363.2	0.16	54.3	0.22	<3.2
NH-878	PD	--	Sept. 5, 2012	6.9	1020	19.2	551	96.6	11.6	4.46	97.6	258	313.7	11.4	171	0.504	3500
NH-881	PD	--	Sept. 5, 2012	7.3	452	23.2	218	54.6	5.47	2.77	24.8	151	183.3	1.11	38.4	0.151	39.1
NH-882	PD	--	Sept. 5, 2012	7.2	705	24.9	374	90.1	7.3	4.52	45	258	312.8	1.97	70.3	0.208	204

Appendix D. R code for statistical analyses

```
data <- read.csv("thmeval.csv", header=T)

attach(data)

data


par(mfrow=c(1,2))

mod1 <-lm(total~CL, data=data)

summary(mod1)

plot(CL,total, xlab="Chloride, ppm", ylab="TTHM, ppb", main="Relationship of
 Chloride \nand Total Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(CL[-c(1,3)]), max(CL[-c(1,3)]))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

abline(h=80, col="red", lty=2)

legend(500,25, col=c("red", "green"), c("EPA MCL for TTHM", "EPA MCL for
 Chloride"), lty=2, cex=0.8)

abline(v=250, col="green", lty=2)


mod1 <-lm(totC~CL, data=data)

summary(mod1)

plot(CL,totC, xlab="Chloride, ppm", ylab="Chlorinated Haloforms, ppb",
 main="Relationship of Chloride and \nTotal Chlorinated Haloforms",
 col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(CL), max(CL))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)


mod1 <-lm(total~ratio, data=data)

summary(mod1)

plot(ratio,total, xlab="Ratio, ppm", ylab="TTHM, ppb", main="Relationship of
 Chloride \nand Total Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(ratio), max(ratio))
```

```
curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

ctext<-function(text, location="topleft"){legend(location, legend=text,
 bty="n", cex=0.5, inset=0.05, pch=NA)}

ctext(text=expression(R^2*'=0.2472, p-value=0.0067, F-statistic'[df=23-
 1]*'=8.879'))


par(mfrow=c(1,2))

mod1 <-lm(total~BR, data=data)

summary(mod1)

plot(BR,total, xlab="Bromide, ppm", ylab="TTHM, ppb", main="Relationship of
 Bromide \nand Total Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(BR), max(BR))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

abline(h=80, col="red", lty=2)

legend("bottomright", col=c("red"), c("EPA MCL for TTHM"), lty=2, cex=0.8)


mod1 <-lm(totB~BR, data=data)

summary(mod1)

plot(BR, totB, xlab="Bromide, ppm", ylab="Brominated Haloforms, ppb",
 main="Relationship of Bromide \nand Brominated Haloforms", col="black",
 pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(BR), max(BR))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)


par(mfrow=c(1,2))

mod1 <-lm(total~IO, data=data, na.omit=T)

summary(mod1)

plot(IO,total, xlab="Iodide, ppb", ylab="TTHM, ppb", main="Relationship of
 Iodide and \nTotal Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(IO), max(IO))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)
```

```
abline(h=80, col="red", lty=2)

legend("bottomright", col=c("red"), c("EPA MCL for TTHM"), lty=2, cex=0.8)


mod1 <-lm(totI~IO, data=data, ma.omit=T)

summary(mod1)

plot(IO, totI, xlab="Iodide, ppb", ylab="Iodinated Haloforms, ppb",
 main="Relationship of Iodide \nand Iodinated Haloforms", col="black", pch=1,
 cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(IO), max(IO))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)


par(mfrow=c(1,3))

mod1 <-lm(total~DOC, data=data5, na.omit=T)

summary(mod1)

plot(DOC,total, xlab="DOC, ppm", ylab="TTHM, ppb", main="Relationship of DOC
 and \nTotal Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(DOC), max(DOC))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

abline(h=80, col="red", lty=2)

legend("bottomright", col=c("red"), c("EPA MCL for TTHM"), lty=2, cex=0.8)


mod1 <-lm(total~NH4, data=data5, ma.omit=T)

summary(mod1)

plot(NH4, total, xlab="NH4, ppm", ylab= "TTHM, ppb", main="Relationship of
 NH4 and \nTotal Trihalomethanes", col="black", pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(NH4), max(NH4))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

abline(h=80, col="red", lty=2)

legend("bottomright", col=c("red"), c("EPA MCL for TTHM"), lty=2, cex=0.8)
```

```
mod1 <-lm(total~CON, data=data5, ma.omit=T)

summary(mod1)

plot(CON, total, xlab="Conductivity, uS", ylab= "TTHM, ppb",
 main="Relationship of Conductivity and \nTotal Trihalomethanes", col="black",
 pch=1, cex=1.2)

coef1 <- coefficients(mod1)

x <- seq(min(CON), max(CON))

curve(coef1[1]+coef1[2]*x, add=TRUE, col="blue", lwd=2.7)

abline(h=80, col="red", lty=2)

legend("bottomright", col=c("red"), c("EPA MCL for TTHM"), lty=2, cex=0.8)
```

Appendix E: Geospatial Methodology and Python Script

Geospatial Methodology

The goal of this geospatial analysis was to collect field data to spatially characterize groundwater aquifer geochemistry throughout the North Carolina Coastal Plain. The locations and utilities selected to sample were determined through analysis of a database which was generated of utilities in coastal North Carolina. The database was generated from information gained from individual utility water quality reports, town and utility websites, as well as phone calls and email conversations with utility operators to gain information for a usable database. This file contains the Water System Name, County and population served, the aquifer tapped, disinfection method, and the most recent TTHM concentration reported in their water quality reports (usually from the last 3 years). Utilities were selected to obtain a variety of aquifers and a various spatial distribution, while maintaining chlorination as a method of disinfection and a population served of over 1000 people.

Initial utility locations were mapped to the best of our ability based off Google Maps Coordinates, in the WGS Web Mercator projection. Once a shapefile was generated, an ArcGIS model was created to select utilities which fit all of our criteria, as discussed in the Methods section of our paper. The python script to the model is provided in the appendix. For each sampling trip (we conducted two, in May and November 2015), once utilities had been contacted and an itinerary was established, an empty shapefile was created and imported into ArcPAD to use for data collection in a Trimble Juno GPS Unit, provided by Duke University. Data were collected at each sampling location including the water utility name, well number, well depth if provided, aquifer tapped, and conductivity recorded in the field.

Field data were incorporated into ArcGIS, and results of chemical testing were attached and input as they became available to generate the maps in Figures 7 through 15 and 22 through 27. Maps were generated comparing each of the constituents believed to lead to increased levels of Disinfection By-products in treated drinking water. One uncertainty cited in this research is the small number of samples collected in total, as well as per aquifer, which limited the trends seen and the geospatial and statistical analyses which could be performed. Few trends were found across aquifers with respect to Chloride, Bromide, and Iodide, however there was a slight trend with location for Dissolved Organic Carbon concentrations.

The data from this research was compared to Aquifer Salinity maps generated by the North Carolina Department of Environmental Quality, with the thought process that if these maps are consistent with our total data (our research in addition to the Outer Banks data and USGS data collected in 2012 and 2013 for the Castle Hayne and Peedee Aquifers in the southern Coastal Plain), these maps could be used to determine utilities from the original database which are expected to have low halide concentrations (Chloride less than the 250 mg/L standard) but still have high reported TTHM concentrations, as suggested locations for future research, or those which should look into DOC concentrations, or see if their Bromide or Iodide concentrations are particularly high compared with Chloride. These shapefiles were generated based on reports from several sources, some of which were over 20 years old, and the web page

does denote these as a “work in progress”. With current USGS data, some discrepancies were noted in the salinity, however this being the most accurate sourced data which could be found, those caveats were noted, and the salinity shapefiles were included to highlight utilities which either are already likely using saline waters and are experiencing high TTHMs, as well as those in areas believed to be fresh, yet are also seeing TTHMs around or above the EPA standard. These maps and ion concentrations were separated by aquifer, with the Upper Cape Fear Aquifer Salinity map being labeled simply as the Cape Fear, because some utilities only provided the Cape Fear Aquifer as a source, while others specifically stated the Upper Cape Fear. All Cape Fear samples were combined, and while the salinity distinction is for the Upper Cape Fear, which varies in salinity and extent with the Lower Cape Fear file, we wanted to avoid mislabeling all samples as coming from the Upper Cape Fear Aquifer.

```
# -*- coding: utf-8 -*-



# ---------------------------------------------------------------------------

# Site_Selection.py

#   (generated by ArcGIS/ModelBuilder)

# Description:

# ---------------------------------------------------------------------------

# Import arcpy module

import arcpy

# Local variables:

Utilities_Database = "Utilities_Database"

Groundwater = "Z:\\MP\\Model\\Groundwater.shp"
```

```
pop_grt_1000 = "Z:\\MP\\Model\\pop_grt1000.shp"

Chlorine_Disinfect = "Z:\\MP\\Model\\Chlor_disinfect.shp"

aquifers = "Z:\\MP\\Model\\aquifers.shp"

TTHM = "Z:\\MP\\Model\\TTHM.shp"

Nine_Utilities = "Z:\\MP\\Model\\Nine_Utilities.shp"

# Process: Selection 1 groundwater source

arcpy.Select_analysis(Utilities_Database, Groundwater, "\"Primary_So\" = 'Ground water'")

# Process: Selection 2 Population

arcpy.Select_analysis(Groundwater, pop_grt_1000, "\"Population\" >1000")

# Process: Selection 3 Chlorine Disinfection

arcpy.Select_analysis(pop_grt_1000, Chlorine_Disinfect, "\"Disinfecti\" = 'Chlorine gas' OR
\"Disinfecti\" = 'Chlorine gas, sodium hypochlorite' OR \"Disinfecti\" = 'Gaseous chlorine' OR
\"Disinfecti\" = 'hypochlorination' OR \"Disinfecti\" = 'hypochlorination and Chlorine gas' OR
\"Disinfecti\" = 'Sodium hypochlorite' OR \"Disinfecti\" = 'Sodium hypochlorite, Chlorine gas (1
well)'")

# Process: Selection 4 Aquifer

arcpy.Select_analysis(Chlorine_Disinfect, aquifers, "NOT \"Aquifer_1\" = 'Fractured bedrock'
AND NOT \"Aquifer_1\" = 'freshwater from Buxton woods and mid-yorktown'")

# Process: Selection 5 TTHM levels
```

```
arcpy.Select_analysis(aquifers, TTHM, "\"F_TTHM__mo\" >30")

# Process: Final Site Selection

arcpy.Select_analysis(TTHM, Nine_Utilities, "\"Water_Syst\" = 'BEAUFORT, TOWN OF' OR \"Water_Syst\" = 'CRAVEN COUNTY WATER SYSTEM' OR \"Water_Syst\" = 'DARE COUNTY WATER SYSTEM' OR \"Water_Syst\" = 'FIRST CRAVEN SANITARY DISTRICT' OR \"Water_Syst\" = 'GATES COUNTY WATER SYSTEM' OR \"Water_Syst\" = 'HARKERS ISLAND SANITARY DIST' OR \"Water_Syst\" = 'ONSLOW WTR AND SEWER AUTHORITY' OR \"Water_Syst\" = 'WILLIAMSTON, TOWN OF' OR \"Water_Syst\" = 'WRIGHTSVILLE BEACH WATER SYST'")
```