PATHOGENIC CONTAMINATION OF PRIVATE WELLS: DISPARITIES IN ACCESS TO SAFE DRINKING WATER IN GASTON COUNTY, NORTH CAROLINA?

by

Alexandra Leigh Alcorn

A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of
Master of Public Health

Charlotte

2018

Approved by:

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Dr. Gary S. Silverman

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Dr. Andrew Harver

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Dr. Elizabeth Racine

ABSTRACT

ALEXANDRA LEIGH ALCORN. Pathogenic contamination of private wells: Disparities in access to safe drinking water in Gaston County, North Carolina? (Under the direction of DR. GARY S. SILVERMAN)

In the United States, groups within the population of private well users may face disparities in access to safe drinking water. Since private well operations and water quality are mostly unregulated, private well users may not be aware when they are consuming contaminated water. The University of North Carolina at Charlotte collaborated with the Gaston County (North Carolina) Department of Health and Human Services- Environmental Health on a program to reduce exposure to water-borne pathogens among private well users. The purpose of the current study was to determine whether private well users in Gaston County face sociodemographic disparities in risk of exposure to pathogenically-contaminated drinking water. We visited the homes of private well users to administer a survey about household sociodemographic characteristics and collect microbial water samples. While the results of the current study reveal no evidence of a relationship between household characteristics and exposure to pathogenically-contaminated drinking water, we did uncover potential disparities in access to safe drinking water between private and public water users. The findings may be used to prioritize future outreach and programming by the Gaston County Department of Health and Human Services; to reduce the risk of exposure to unsafe drinking water among private well users in Gaston County; and, to further inform the environmental health community about potential environmental justice issues among private well users.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Gary S. Silverman from the Department of Public Health Sciences at the University of North Carolina at Charlotte, for his steady and invaluable guidance throughout the research and thesis-writing process.

I would like to thank Dr. Wenwu Tang from the Center for Applied GIScience at the University of North Carolina at Charlotte, Dr. Eric Delmelle from the Department of Geography & Earth Sciences at the University of North Carolina at Charlotte, and Ms. Samantha Dye of the Gaston County Department of Health and Human Services for their crucial input and support during the development and implementation of the current study. I would also like to thank Claudio Owusu, Doctoral student with the Department of Geography & Earth Sciences at the University of North Carolina at Charlotte, and Yu Lan, Geography Masters Student with the Department of Geography & Earth Sciences at the University of North Carolina at Charlotte, for their technical assistance in developing the survey for and applying GIScience techniques to the current study.

Finally, I would like to thank Carolyn Akhimiomoh, Donna Blekfeld-Sztraky, Sabahat Siddiq, Ikram Chaudhary, Munachiso Okechukwu, Ellana Valladares, Alicia LaLoggia, Joshua Runfola, Mitchell Yokeley, Adam Lone, Kenley Triplett, and Ryan Gibson with the University of North Carolina at Charlotte for their assistance in data collection. The current study would not have been possible without their dedication to the project.

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CHAPTER 1: INTRODUCTION

Access to safe drinking water is essential to protect and promote public health (Centers for Disease Control and Prevention, 2015). Water helps the human body lubricate joints, normalize body temperature, protect sensitive tissues, and get rid of wastes (Centers for Disease Control and Prevention, 2016). Water is involved in heart function and distribution of blood in the body. Dehydration may result in reduced cognitive performance (such as reduced memory and psychomotor skills), reduced physical performance (such as endurance), and the development of headaches (Popkin, D'Anci, & Rosenberg, 2010).

Despite having one of the world's safest drinking water supplies (Centers for Disease Control and Prevention, 2014), there has been renewed interest and concern over drinking water quality in the United States following the water crisis in Flint, Michigan in which a change in the drinking water supply source in 2014 resulted in elevated levels of lead in the drinking water. Socioeconomically disenfranchised communities were the most impacted by the failure, bringing to light environmental justice concerns in access to safe drinking water (Bellinger, 2016; Campbell, Greenberg, Mankikar, & Ross, 2016; Greenberg, 2016; Patel & Schmidt, 2017).

Even though the municipal water supply in the United States is one of the safest in the world, private wells are not as strictly monitored as municipal water systems (Center for Disease Control and Prevention, 2010) and are a cause for concern regarding potential contamination (Centers for Disease Control and Prevention, 2009). Private well water may become contaminated by naturally-occurring chemicals, such as arsenic and radon, synthetic chemicals, and pathogens from fecal matter (Centers for Disease Control and Prevention, 2009). Water contaminated by feces may contain harmful parasites, bacteria, or viruses, presenting an immediate human health hazard (Division of Enviromental Public Health, 2016). Pathogenic well water contamination occurs when pathogens enter the aquifer through surface water infiltration, or are released from underground sources, due to poor land use practices, improper storage of livestock manure, septic tank failure, septic leach fields, leaky sewer lines, and sinkholes (US Environmental Protection Agency, 2016).

Approximately 15 million people in the United States drink water from private wells (US Environmental Protection Agency, 2016). Private well contamination is a public health concern because contaminated water may go undetected, and private well users may be drinking contaminated water without being aware of the health threat. The leading cause of disease outbreaks from private wells in the United States is Hepatitis A, which causes a liver infection, followed by *Giardia*, *Campylobacter*, *E. Coli*, *Shigella*, *Cryptosporidium*, and *Salmonella*— all of which cause diarrheal disease (Centers for Disease Control and Prevention, 2015). Children, the elderly, and immunocompromised individuals are at increased risk of illness following exposure to waterborne pathogens (Rogan, Brady, Committee on Environmental Health, & Committee on Infectious Diseases, 2009; US Environmental Protection Agency, 2017c).

1.1 Private well water testing

National guidelines recommend using a bacterial indicator to test well water annually for pathogenic contamination (Center for Disease Control and Prevention, 2010). Wells should also be inspected each year for mechanical problems, since issues such as cracked well casing render a well more susceptible to entry by pathogens

(Centers for Disease Control and Prevention, 2010). Many well users are not aware of these recommendations or choose not to test their wells (Centers for Disease Control and Prevention, 2015; NC Department of Health and Human Services, 2016).

Pathogens in water can be detected using bacterial indicators such as total coliform and *E. coli* (Division of Enviromental Public Health, 2016). Total coliform is a group of bacterial strains that exist naturally in the environment and human waste. Fecal coliform, a subgroup of total coliform, occur more exclusively in the feces of warm-blooded animals and include strains such as *E. coli*. While total and fecal coliform bacteria do not typically cause illness, the presence of these bacterial strains may indicate fecal contamination of water (Division of Enviromental Public Health, 2016).

1.2 Private well water regulations

The Safe Drinking Water Act is a federal law regulating public water systems. Although the Safe Drinking Water Act does not apply to private wells, it sets useful health-protective standards for evaluating private well water quality (US Environmental Protection Agency, 2017e). Under the Safe Drinking Water Act, the Environmental Protection Agency establishes maximum contaminant levels to denote the threshold level of a contaminant that may be present in a public water system. The Maximum Contaminant Level for total coliform (including *E. coli*) is zero, although public water systems are only in violation if they find total coliform in more than five percent of samples in a month (US Environmental Protection Agency, 2017d). Under public water system guidelines, a positive total coliform or *E. coli* test requires additional testing. Repeat positive tests indicate that the water may be unsafe for drinking. The presence of total coliform without *E. coli* is a less definitive indicator of pathogenic contamination than when *E. coli* is present (Center for Disease Control and Prevention, 2010; US Environmental Protection Agency, 2013).

State and local private well regulations that exist are usually limited in scope, such as regulating the period during construction and installation of the well (US Environmental Protection Agency, 2016; US Environmental Protection Agency, 2017e). A 2008 North Carolina law (15A-NCAC-18A C.F.R. § 3801-3805) requires local health departments to conduct bacterial and chemical contaminant testing within 30 days of completion for all newly constructed water wells. After the initial construction period, there are no state requirements regarding well testing (NC Department of Health and Human Services, 2016; US Environmental Protection Agency, 2016). In most states and localities, private wells are not under government regulatory purview. It is up to well users to make decisions regarding the maintenance, testing, and servicing of their wells, as well as the treatment of their wells when contaminated (Centers for Disease Control and Prevention, 2015; NC Department of Health and Human Services, 2016).

1.3 Magnitude of pathogenic contamination of well water

Groundwater serves as a primary drinking source for more than 3 million North Carolinians (NC Department of Health and Human Services, 2016). Yet between 2000-2010, less than 200,000 private wells in North Carolina were tested for contaminants. In Gaston County, North Carolina, where an estimated 8,000 private wells serve approximately 42% of the population, there are currently no data on the number of wells that have been tested for bacterial contamination (NC Department of Health and Human

Services, 2016). The magnitude of the health threat due to pathogenic contamination of private well water across North Carolina and in Gaston County is currently unknown. Nonetheless, data from research studies provide important estimates of pathogenic contamination of well water.

Nationally, an estimated 23-78% of private wells are contaminated with total coliform while 2-10% have detectable levels of *E. Coli* (Allevi, Krometis, Hagedorn et al., 2013; Borchardt, Bertz, Spencer, & Battigelli, 2003; DiSimone, Hamilton, & Gilliom, 2009; Fong, Mansfield, Wilson et al., 2007; Gonzales, 2008). Based on more conservative national *E. coli* estimates, between 300,000 and 1.5 million households in the United States are potentially exposed to disease-causing pathogens. In Gaston County, between 160 and 800 households with private wells in Gaston County may be exposed to *E. coli*, placing thousands of residents at risk of waterborne illness.

The most recent national surveillance report on waterborne disease outbreaks revealed that between 2011-2012, zero water-related disease outbreaks from private well contamination were reported to the Center for Disease Control and Prevention (Beer, Gargano, Roberts et al., 2015). Yet between 1971-2000 the Centers for Disease Control and Prevention estimated that individual water systems, mostly private wells, were responsible for approximately 3% of all reported waterborne disease outbreaks (Craun, Craun, Heberling et al., 2007). These outbreaks resulted in approximately 18,000 cases of waterborne illness, 135,000 sick person-days, 1,260 visits to a physician, 707 emergency department visits, 177 hospitalizations, and 1 death. The total monetary impact for medication, doctor and emergency room visits, hospitalizations, ill productivity losses, and caregiver productivity losses amounted to over $6.05 million (Craun et al., 2007). In

North Carolina, approximately 29,200 emergency department visits occur each year due to acute gastrointestinal illness caused by pathogenic contamination of well water (*95% CI, 26,500-31,900*). The annual cost of these cases is an estimated $39.9 million (*95% CI, $2.56 million-$192 million*) (DeFelice, Johnston, & MacDonald Gibson, 2016). These outcomes represent an unnecessary health and monetary impact to private well users, since waterborne disease and illness is largely preventable.

Morbidity and mortality reports for waterborne disease outbreaks are likely underestimated due to various limitations in data collection and surveillance (Craun et al., 2007). Many waterborne diseases, illnesses, and outbreaks are unrecognized and unreported. The reliability of reporting depends on several factors, including public awareness, medical help-seeking behaviors of the infected persons, the availability and reliability of laboratory services, local reporting requirements, and the operational capacity of state and local surveillance and investigative agencies. Surveillance is often passive, and reporting is not mandatory for many waterborne diseases. Case definitions may vary between states and localities (Craun et al., 2007). Consequently, the true public health burden of private drinking water contamination is probably much more severe than current estimates.

1.4 Social determinants of access to safe drinking water

Marginalized communities frequently face disparities in access to safe drinking water, presenting a potential environmental justice issue (Balazs & Ray, 2014; Greenberg, 2016; Heaney, C., Wilson, Wilson et al., 2011; Heaney, C.D., Wing, Wilson et al., 2013; Stillo & MacDonald Gibson, 2017; Switzer & Teodoro, 2017). The

Environmental Protection Agency defines environmental justice as, "*…the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies*" (US Environmental Protection Agency, 2017b).

Since public water has been shown, in many cases, to be safer for drinking than private water (Heaney, C. et al., 2011; Heaney, C.D. et al., 2013; Stillo et al., 2017), infrastructural disparities may lead to disparities in exposure to unsafe drinking water. Low-income and racial minority communities in rural areas often lack connections to municipal services due to local annexation and zoning policies, relying on less strictly monitored private well drinking water (Aiken, 1987; Balazs et al., 2014; Heaney, C. et al., 2011; Licther, Parisi, Grice, & Taquino, 2007; MacDonald Gibson, DeFelice, Sebastian, & Leker, 2014; Wilson, Heaney, Cooper, & Wilson, 2008).

Older studies show that in rural communities, economically and educationally disenfranchised households are at a higher risk of exposure to water that tests positive for total coliform (Calderon, Johnson Jr., Craun et al., 1993). These findings include residents who drink water from both community and municipal systems. Disparities in access to safe drinking water also exist among the population of municipal water drinkers, with race/ethnicity and socioeconomic status predicting drinking water quality (Switzer et al., 2017).

While the existing literature reveals disparities in access to safe drinking water among households in rural communities and municipal water drinkers, there is a gap in the literature regarding disparities in access to safe drinking water among private well users (Fox, Nachman, Anderson, Lam, & Resnick, 2016; VanDerslice, 2011). This study filled in the gap in the literature regarding whether specific sociodemographic groups among the population of private well users face disproportionate exposure to unsafe drinking water.

1.5 Research aim and significance

The aim of this study was to examine the relationship between household characteristics of private well users and pathogenic contamination of private wells in Gaston County, North Carolina to: (a) drive future private well programming by the Gaston County Department of Health and Human services; and, (b) examine potential environmental justice issues in access to safe drinking water among private well users. The relationship between household demographic and socioeconomic characteristics ("household characteristics") and private well water quality is of particular concern in Gaston County due to its relatively low median household income, high percentage of persons in poverty, and low rates of educational attainment (Table 1) (US Census Bureau, 2017).

Table 1.

Demographic and socioeconomic characteristics of Gaston County (North Carolina) and North Carolina

Variable	Gaston County	North Carolina
Population estimates	216,965	10,146,788
Persons under 5 years, percent	6.0	6.0
Persons 65 years and over, percent	15.5	15.5
White alone, percent	79.2	71.0
Black or African American alone, percent	16.7	22.2
American Indian and Alaska Native alone, percent	0.5	1.6
Asian alone, percent	1.5	2.9
Native Hawaiian and Other Pacific Islander alone, percent	0.1	0.1
Two or more races, percent	1.9	2.2
Hispanic or Latino, percent	6.8	9.2
Median value of owner-occupied housing units, in USD	125,100	154,900
High school graduate or higher, percent of persons age 25 years+	82.9	85.8
Bachelor’s degree or higher, percent of persons age 25 years+	19.0	28.4
With a disability, under age 65 years, percent	12.1	9.6
Persons without health insurance, under age 65 years, percent	13.0	13.1
Median household income (in 2015 dollars)	22,828	25,920
Persons in poverty, percent	17.3	16.4

Source: US Census Bureau, 2017

It is currently unknown whether there are disparities in access to safe water among private well users in Gaston County. I designed the current study to assess household characteristics of private well users to determine whether specific groups are at a higher risk of exposure to pathogenically-contaminated well water. I examined social determinants of exposure to pathogenically-contaminated drinking water as measured by socioeconomic status (income, education, and owner-occupied household), race, and ethnicity. I also examined potential determinants of behaviors toward well testing, maintenance, and treatment, which would impact risk of exposure to waterborne pathogens: at least one individual under the age of 18 in the household, at least one individual over the age of 65 in the household, and length of time lived in the household.

CHAPTER 2: LITERATURE REVIEW OF EXPOSURE TO CONTAMINATED DRINKING WATER

2.1 Water disparities and environmental justice

Disproportionate exposure to contaminated water occurs through actions at the infrastructure and policy levels. Marginalized communities often suffer the adverse impacts of political power imbalances (Heaney, C. et al., 2011), institutional discrimination, socioeconomic inequality, and economic marginalization— forces which lead to segregation through housing policy, investment patterns, infrastructure planning, industrial siting, zoning (Heaney, C. et al., 2011), racially-segregated labor markets, and economic restructuring (Morello-Frosch, 2002). Polluting facilities and activities are often sited in marginalized communities (Balazs et al., 2014; Calderon et al., 1993; Heaney, C. et al., 2011; Heaney, C.D. et al., 2013; Stillo et al., 2017; Wilson, 2009; Wilson et al., 2008). Exposure may occur through irregular enforcement of codes and regulations promulgated by the Safe Drinking Water Act, inconsistent management of small water systems due to poor managerial and operational capacity, or lack of coordination between government agencies (Balazs et al., 2014; Calderon et al., 1993; Heaney, C.D. et al., 2013; Naman & MacDonald Gibson, 2016; Wilson et al., 2008). Discriminatory local annexation policies leave some communities without access to municipal water and sewer services (Balazs et al., 2014; Calderon et al., 1993; Heaney, C. et al., 2011; Heaney, C.D. et al., 2013; Naman et al., 2016; Stillo et al., 2017; US Census Bureau, 2008; Wilson, 2009; Wilson et al., 2008), representing an environmental injustice due to the differences in water quality between public and private water systems.

2.2 Public versus private water quality

Private well water is more likely than public water to be contaminated (VanDerslice, 2011). For example, in Orange County, North Carolina, private well water was more likely than municipal water to exceed at least one national drinking water standard ($p=0.0001$) (Heaney, C.D. et al., 2013). In Wake County, North Carolina, private well water was more likely to test positive for bacterial strains than municipal water ($p \leq 0.001$) (Stillo et al., 2017). Disparities in access to safe drinking water may result in health disparities. Researchers estimate that connecting a sample of 1,010 households in Wake County, North Carolina to municipal water would reduce well water-attributable acute gastrointestinal emergency department visits by 22% annually (Stillo et al., 2017). Rural populations disproportionately rely on private wells for drinking water, bearing the consequential burden of waterborne illness.

2.3 Exclusion from the public water supply

Within the population of rural private well users, certain groups are more likely than other to be excluded from municipal services. “Municipal under-bounding” describes the phenomenon by which economically marginalized and racial minority populations in rural areas often live on the edges of municipalities, called extraterritorial jurisdictions, where residents are denied access to municipal water and sewer services (Aiken, 1987; Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., Snipes, M. , 2011; Johnson, Parnell, Joyner, Christman, & Marsh, 2004; Licther et al., 2007; Stillo et al., 2017). Residents living in extraterritorial jurisdictions frequently rely on wells which may be old, located close to septic systems, or improperly maintained, placing the wells at higher risk of contamination. For example, within Wake County, North Carolina census tracts, the proportion of the population that is African American is positively associated with the odds of exclusion from public water access (MacDonald Gibson et al., 2014). In the Lower Yakima Valley of Washington State, more than 20% of the population lives in poverty, 30% have less than a high school education, and the proportion of the population that is Hispanic/Latino or Native American is higher than the state average. Approximately 34% of the population resides in extraterritorial jurisdictions without access to public water (Washington State Department of Agriculture, Washington State Department of Ecology, Washington State Department of Health, Yakima County Public Works Department, & US Environmental Protection Agency, 2010).

2.4 Well testing behaviors of private well users

Well testing, maintenance, and treatment behaviors of private well users impact well users' awareness of potential contamination issues, as well as the users' ability to mitigate any issues that may arise. Studies of well users in Canada and the United States show that most well users do not test their wells according to government guidelines (Flanagan, Marvinney, & Zheng, 2015; Jones, Dewey, Dore et al., 2005; Kreutzwiser, de Loe, Imgrund et al., 2011; Malecki, Schultz, Severtson, Anderson, & VanDerslice, 2017). Only 7-8% of well users regularly test their well water (Flanagan et al., 2015; Jones et al., 2005), and many only test after purchasing a home (Flanagan et al., 2015). Despite a lack of regular testing, many well users report trusting the safety of their water supply. Even among those who do not trust the safety of their water supply, many still do not regularly test their private well water supply (Jones et al., 2005).

Well testing behavior may be associated with select household characteristics, including length of time lived in the home, age of the resident, educational attainment (Flanagan et al., 2015), and the presence of children living in the home (Malecki et al., 2017). In Maine, Flanagan et al. (2015) found that the longer the residents lived in the home, the less likely they were to have tested their well within the last five years. As age of the resident increased, intention to test the well decreased. Higher educational attainment of the resident was associated with increased odds of having tested with well within the last five years (Flanagan et al., 2015). In Wisconsin, Malecki et al. (2017) found that more children living in the home were associated with higher odds of having tested the well within the last ten years. Flanagan et al. (2015) also found that social norms play a role in testing behavior: when testing for arsenic, well users who knew their neighbor completes regular well testing were more likely to include a test for arsenic in their own monitoring activities.

Well users report a variety of barriers to regular well testing: low perceived threat (Malecki et al., 2017); low perceived vulnerability; perceived testing norms of neighbors; remembering to test (Flanagan et al., 2015); complacency (Jones et al., 2005; Kreutzwiser et al., 2011); lack of knowledge about testing recommendations (Jones et al., 2005; Kreutzwiser et al., 2011; Malecki et al., 2017); inconvenience (Jones et al., 2005; Kreutzwiser et al., 2011); cost (Flanagan et al., 2015; Kreutzwiser et al., 2011); and government privacy concerns (Jones et al., 2005; Kreutzwiser et al., 2011). Some well users perceive that their water is safe to drink if it is odorless, has a good taste, and is clear (Jones et al., 2005). Negative well test results in the past may also reduce the likelihood that a well user will conduct a well water test (Jones et al., 2005).

2.5 Conceptual framework

The current study was guided by the Drinking Water Disparities Framework (Figure 1) (Balazs et al., 2014).

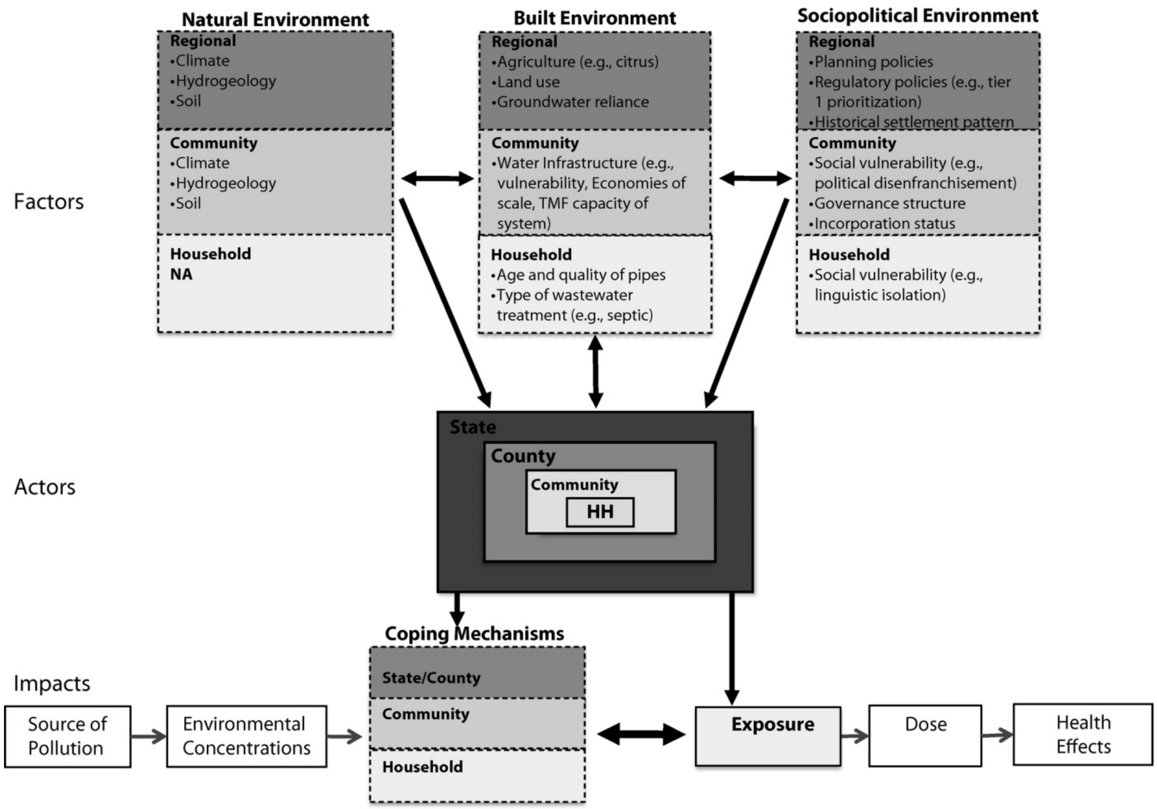

Figure 1. Drinking Water Disparities Framework (Balazs et al., 2014)

Building on previous environmental justice frameworks, the Drinking Water Disparities Framework is unique in acknowledging the social, political, historical, and structural factors that influence drinking water disparities (VanDerslice, 2011; Wilson, 2009). The Drinking Water Disparities Framework posits that discrimination by race, class, and other sociodemographic characteristics is embedded in institutional actors and processes, resulting in marginalized communities bearing a disproportionate burden of exposure to contaminated water. Household characteristics also determine coping mechanisms, or the ability of the household to mitigate environmental hazards to reduce risk of exposure (Balazs et al., 2014). As applied to the proposed study, it was expected that: (a) certain households are at a higher risk of pathogenic well contamination because institutional discrimination places specific groups at a higher risk of exposure to environmental hazards; and, (b) household characteristics are related to community and household coping mechanisms and, in effect, risk of exposure to contaminated drinking water.

I adapted the Drinking Water Disparities Framework to include the specific variables of interest for the current study, modifying the original framework by re-arranging the relationships between levels and actors (Figure 2).

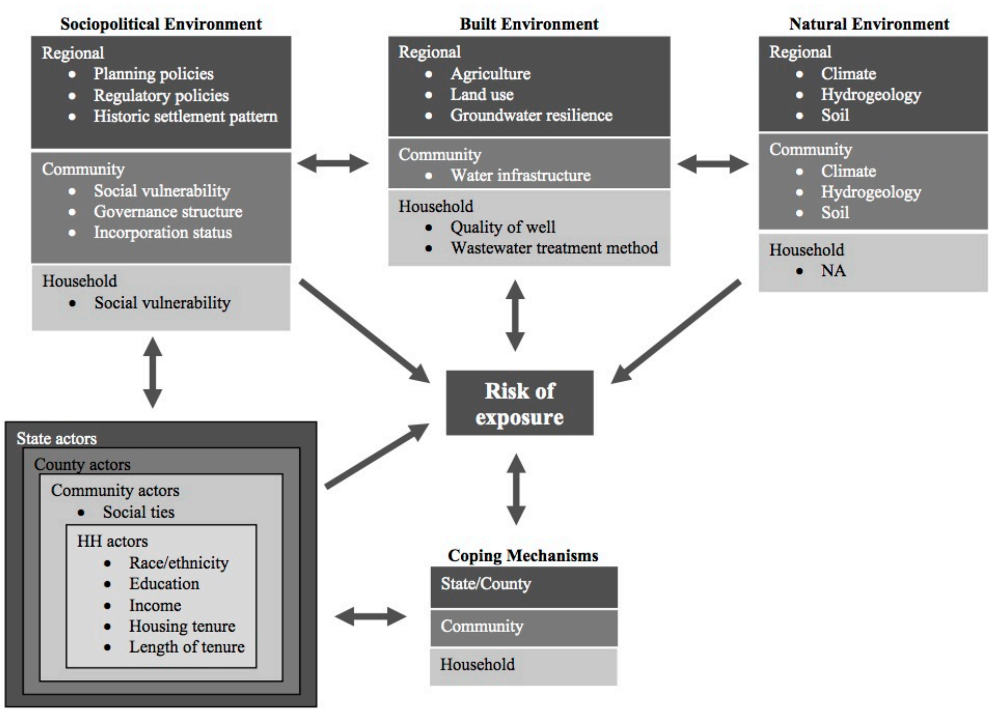

Figure 2. Modified Drinking Water Disparities Framework (Balazs et al., 2014)

By placing risk of exposure at the center of the framework, as opposed to the peripheral position as seen in the original framework, the focus of the framework shifts from actors to outcomes. Risk of exposure takes a more proximate position to the sociopolitical, built, and natural environments, showing the processes by which these environments can act on the risk of exposure directly, or through actors. Coping mechanisms also take a more proximate position to the environments since coping mechanisms may be influenced by multiple actors and conditions. I adopted a circular layout, rather than tiered, to approximate the complex and dynamic nature of the relationships and interactions included in the framework.

2.6 Implications of existing literature

Private well water is more likely than public water to be contaminated (DeFelice et al., 2016; Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., Snipes, M. , 2011; Heaney, C.D. et al., 2013; Stillo et al., 2017). Whether due to a paucity of private well regulations, discriminatory zoning patterns and annexation policies, or a multitude of other factors, disparities in access to safe drinking water have been shown to follow sociodemographic patterns. While several studies have evaluated the community-level relationship between sociodemographic characteristics and private well water quality, very few have examined these relationships at the household level (Aiken, 1987; Balazs et al., 2014; Calderon et al., 1993; Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., Snipes, M. , 2011; Heaney, C.D. et al., 2013; Johnson et al., 2004; Licther et al., 2007; Stillo et al., 2017; Switzer et al., 2017; US Census Bureau, 2008; Wilson, 2009). The current study addressed gaps in the existing literature regarding the relationship between household characteristics and pathogenic well water contamination, as well as environmental justice issues among the population of private well users.

CHAPTER 3 HYPOTHESES

To analyze the relationship between household characteristics and bacterial well water contamination, I tested eight hypotheses.

> Null hypothesis 1: There is no relationship between bacterial well water quality and the presence of least one individual under the age of 18 in the household.
>
> Null hypothesis 2: There is no relationship between bacterial well water quality and the presence of at least one individual age 65 or older in the household.
>
> Null hypothesis 3: There is no relationship between bacterial well water quality and annual household income.
>
> Null hypothesis 4: There is no relationship between bacterial well water quality and highest level of education completed in the household.
>
> Null hypothesis 5: There is no relationship between bacterial well water quality and race of the household.
>
> Null hypothesis 6: There is no relationship between bacterial well water quality and ethnicity of the household.
>
> Null hypothesis 7: There is no relationship between bacterial well water quality and length of time lived in home.
>
> Null hypothesis 8: There is no relationship between bacterial well water quality and home ownership.

CHAPTER 4 METHODS

4.1 Study design and data source

I conducted a cross-sectional study to determine the strength of association between household characteristics and possible pathogenic contamination of well water by surveying a sample of the population in Gaston County that uses private wells. The study was an add-on to a larger effort (henceforth "Healthy Wells") to improve county private well services in Gaston County. Healthy Wells, a partnership between the University of North Carolina at Charlotte and the Gaston County Department of Health and Human Services- Environmental Health, involves students from the University of North Carolina at Charlotte who visit the households of private well users in Gaston County. At the households, the students (henceforth "interviewers") deliver risk communication materials about well maintenance, collect a well water sample for bacterial testing, and collect coordinates and take photographs of the well.

4.2 Study population

The study population was composed of households with private wells in Gaston County. To participate in the study, the consenting individual needed to be at least 18 years of age, consider the household her or his primary residence, and speak English. Households that use well water exclusively for yard irrigation, that drink municipal water, or are connected to a community well were excluded from the study.

4.3 Sample size and power

I used an alpha (α) level of significance of 0.05 for statistical tests. The power level (β) for this study was 0.95. I calculated sample size using G*Power 3.1 for Mac OS X, a free, noncommercial power analysis software for statistical tests developed by researchers from the Heinrich-Heine-Universität Düsseldorf (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007). I used G*Power 3.1 to compute an a priori power analysis for χ^2 tests. First, I employed a distribution-based approach for the χ^2 test statistic. Next, I chose a goodness-of-fit test for contingency tables (Faul et al., 2007). For contingency tables and goodness of fit tests, G*Power 3.1 performed calculations using the following equations, in which π_I is the probability of success in group i, Σ is the population variance-covariance matrix, λ is the non-centrality parameter of the non-central χ^2 distribution, and N is the total sample size:

Hypothesis: $\pi_{1i} = \pi_{0i}$
$i = 1, \ldots, k$
$\sum_{i=1}^{k} \pi_{0i} = 1$

Effect size: $w = \sqrt{\sum_{i=1}^{k} \frac{(\pi_{1i} - \pi_{0i})^2}{\pi_{0i}}}$

Non-centrality parameter: $\lambda = w^2 N$

To detect potential differences between groups and achieve an effect size of 0.3, a significance level of $\alpha = 0.05$, and a power level of $\beta = 0.95$ with nine degrees of freedom, this study required a total sample size of 271 participants.

4.4 Sampling methods and recruitment

I used stratified random sampling to select a sample of low-, medium-, and high-socioeconomic census tracts. I operationalized socioeconomic status through educational attainment, as measured by the percent of the census tract population ages 25 or older who are high school graduates or higher, including equivalency (US Census Bureau, 2014). Education represented socioeconomic status for sampling methods, rather than wealth, occupation, or income, because measures of education typically have higher response rates than income and are easier to measure than wealth or occupation (Shavers, 2007). Education is a more stable measure of socioeconomic status, as it is not subject to fluctuations from life events after early adulthood, is less age-dependent than other measures, and is less likely than income and occupation to be affected by poor health status later in life (Shavers, 2007). I selected the stratified random sampling method because it would yield a representative sample of households with varying sociodemographic characteristics.

To select the sample, I sorted Gaston County census tracts from low to high values based on the percent of adults ages 25 or older who are high school graduates or higher, including equivalency. I then divided the list of census tracts into three equal subgroups. To achieve equal subgroups, I removed two census tracts from the sampling frame. The census tracts with the lowest and highest levels of educational attainment were removed, leaving sixty-three census tracts in the sampling frame. Each subgroup had twenty-one census tracts. I then utilized a random number generator to randomly select census tracts from each subgroup. I randomly selected census tracts in each sub-group until each strata contained approximately the same number of households.

Interviewers visited census tracts in the order in which the tracts were selected by the random number generator. The order in which interviewers visited the households in each selected census tract was based on convenience, and the interviewing teams visited or attempted to visit each household with a private well in all selected census tracts. Interviewer teams remained relatively stable throughout recruitment, with the only changes in student groups occurring when students requested time off. Stable pairings allowed me to rotate student groups weekly through low-, medium-, and high-socioeconomic status census tracts to minimize interviewer bias. For example, if Group 1 went to low-socioeconomic status census tracts for data collection during week one, the same group was then sent to medium-socioeconomic status census tracts during week two and high-socioeconomic status census tracts during week three.

4.5 Variables and rationale

To analyze the relationship between household characteristics and drinking water quality, I compared one dependent variables with multiple independent variables. I chose the dependent variable, total coliform contamination, to represent drinking water quality because the Environmental Protection Agency uses total coliform to measure pathogenic quality of public water (US Environmental Protection Agency, 2013).

I chose five independent variables to measure household characteristics based on their demonstrated importance as social determinants of health in the environmental justice literature, as the variables may place the household at higher risk of exposure to contaminated drinking water (Calderon et al., 1993; Heaney, C.D. et al., 2013; Stillo et al., 2017): annual household income; highest level of educational attainment in the household; home ownership (renter or owner); race; and ethnicity. Annual household income, highest level of educational attainment in the household, and home ownership serve as proxies for socioeconomic status (Macintyre, Ellaway, & Cummins, 2002; Shavers). I anticipated that higher income and educational attainment would be associated with safe drinking water, and that well users who own their home would be more likely to have safe water because home ownership represents an economic resource.

I chose the remaining independent variables due to their potential influence on well testing behavior (Flanagan et al.; Malecki et al., 2017): the presence of at least one individual under the age of 18 in the household, the presence of at least one individual age 65 or over in the household, and length of time lived in the home. Residents who are more likely to test their wells (those with more children in the house, those older in age, and those who have recently purchased their homes) may be more likely to treat their wells, reducing the likelihood that the residents will be exposed to pathogenically-contaminated drinking water. Within the Drinking Water Disparities Framework, well testing represents a household coping mechanism that reduces the risk of exposure.

4.6 Measurement and instrument

I collected household characteristic data using the Household Characteristics Survey (Appendix A: Household characteristics survey). A graduate student in the Department of Geographic Information Services at the University of North Carolina at Charlotte used the software package Microsoft Visual C# to create an electronic version of the survey. Interviewers administered the survey face-to-face using Juniper Systems Mesa 2® tablets.

During the first weeks of data collection (October 29, 2017 through December 2, 2017), the survey was administered as a self-paced electronic survey completed by respondents. Respondents could opt to respond to survey questions administered verbally by the interviewers. Any technical assistance or verbal assistance provided was recorded by interviewers. To improve survey response rates, we changed the data collection protocol on December 3, 2017 to require interviewers to administer the survey verbally to participants. The response rates did not change significantly after we changed the data collection protocol ($\chi^2 = 16.1525, p = 0.095$).

The bacterial well water tests were processed at the Gaston County Department of Health and Human Service- Environmental Health laboratories. Total coliform well water contamination was measured as a binary variable, classified as “positive” or “negative”. *E. coli* was also reported as “positive” or “negative”. I measured five independent variables— presence of at least one individual under the age of 18, presence of at least one individual age 65 or older, race, ethnicity, and home ownership—as nominal variables, and I measured annual household income as an ordinal variable. After measuring educational attainment and length of time lived in the home as continuous variables, I recoded the variables as ordinal variables. I measured education and length of time lived in the home as continuous variables to maintain flexibility of the data for additional analyses for Gaston County Department of Health and Human Services-Environmental Health.

4.7 Reliability

I expect this study to have good reliability if repeated in Gaston County or another rural county. As a certified facility, the county laboratory is responsible for providing reliable test results. Therefore, the bacterial test results should have provided an accurate analysis of private well water quality. I attempted to eliminate systematic error in various ways. First, I minimized interviewer bias during survey administration by rotating interviewers weekly through neighborhoods with different socioeconomic levels. Second, I provided interviewers with a script to follow during data collection (Appendix B: Recruiting script). Third, I trained interviewers to read the survey questions and responses exactly as written. Nonetheless, it is possible that systematic error was introduced during data collection due to differences in verbal administration of the survey by the interviewers.

Despite attempts to eliminate systematic errors, it is possible that the change in survey mode introduced systematic bias into the current study. As previously stated, on December 3, 2017 the interviewers stopped offering well users the option to complete the survey using the handheld tablet after learning that private well users disliked using the handheld tablets. There was no significant change in response rates. Prior to the change in protocol, the interviewers took note of whether they read any of the questions and responses aloud or provided study participants with technical assistance. Verbal or technical assistance was not significantly associated with total coliform results ($\chi^2 = 2.7507, p = 0.253$). The change in the data collection protocol is not expected to have greatly impacted the reliability of the current study.

4.8 Validity

Environmental justice frameworks show that the relationship between household characteristics and environmental exposures is complex, influenced by various actors at multiple socioecological levels (Faul et al., 2009). Despite the wide range of potential confounders, household characteristics may play an important role in predicting disproportionate exposure to waterborne pathogens.

I expect this study to have good external validity since it should be generalizable to other rural areas in which households rely on private well drinking water. The sample is expected to be representative since I utilized a stratified sampling method to select participants from various sociodemographic groups. Groundwater quality and contamination risk have been shown to vary regionally, so attempts should be made to replicate the results in other regions of the United States (Beer et al., 2015).

The sociodemographic questions on the Household Characteristics survey are expected to have good construct validity since demographic and socioeconomic data are typically used to represent disparities related to group identity in the environmental justice literature (Calderon et al., 1993; Heaney, C.D. et al., 2013; Stillo et al., 2017). Total coliform is expected to have good construct validity since it reveals potential exposure to pathogenic contaminants.

4.9 Data analysis plan

I analyzed the data using Stata® and did not include survey non-responses in the analysis. I sorted continuous variables (highest level of educational attainment in the household and years lived in the household) into categories for data analysis. I sorted highest level of educational attainment, measured in years, into less than high school (>12 years), high school graduate or equivalency (12 years), some college or Associate degree (<12 and ≥15 years), Bachelor degree or equivalency (<15 and ≥16 years), and higher than a Bachelor degree (<16). I sorted length of time lived in the home into 2-year time frames, starting with 0-1 years and up to 9 years. I sorted ten years or more into one category. I conducted Pearson's chi-squared (χ^2) test for independence for each independent variable to test for significant associations between variables.

4.10 Ethical issues and human subject protection

The proposed study was approved as exempt by the University of North Carolina at Charlotte Institutional Review Board (IRB #17-0252) due to the minimal amount of risk presented by the data being collected. For the protection of human subjects, only adults were eligible to participate in the study. Each participating household was identified by its unique well permit identification number. During data analysis, the results of the Household Characteristics survey were stored on a master database along with total coliform well water test results. The master database was available for access to myself, the principle investigators, and the graduate students working on the project.

4.11 Significance

Following the water quality crisis in Flint, Michigan, public health practitioners have called for a renewed sense of urgency regarding access to safe drinking water in the United States (Bellinger, 2016; Campbell et al., 2016; Greenberg, 2016; Patel et al., 2017). The current study addressed the Environmental Protection Agency's

Environmental Justice 2020 challenge of ensuring that all people have access to drinking water that meets national health-based standards (US Environmental Protection Agency, 2017a). The current study will be significant for the public health community because it will uncover whether there are household disparities in access to safe drinking water among well users in Gaston County, North Carolina. If disparities are uncovered, it may signal that there are widespread disparities in access to safe water among well users on a national scale— information which will be crucial in setting priorities for private well services and establishing local, state, and national environmental regulatory policies. Not only will the current study clarify the research community's understanding of characteristics of private well users to improve planning and implementation of outreach programs, but the study may also better ensure equitable access to safe drinking water for private well users.

CHAPTER 5: RESULTS

5.1 Response Rates

We conducted recruitment and field work between October 29, 2017 and February 25, 2018, visiting or attempting to visit a total of 1,899 properties (Table 2).

Table 2.

Visit results from sample in Gaston County, North Carolina

Visit result	n	% of available households	% of total population
Available households			
Participated in research	138	21	7
Participated in Healthy Wells, but not in research	228	35	12
Declined to participate	228	35	12
Requested that we visit at a later date	62	9	3
Total available units	**656**	**100**	**34**
Unavailable households			
Did not qualify	22	---	1
Did not answer the door	680	---	36
No entry onto property	538	---	28
Missing data	3	---	---
Total population	**1,899**	**---**	**100**

Out of 656 residents who met the inclusion criteria and whom we invited to participate in the current study, a total of 138 households agreed to participate in the current study (Table 2). The response rate was 21%. A total of 228 households participated in the Healthy Wells project but did not participate in this study, either because they did not consent or did not complete both the survey and well testing. Another 228 households declined to participate in both the Healthy Wells project and the current study. Twenty-two households did not meet inclusion criteria, 680 households did not answer the door, and we were unable to enter the property of 539 households. We have missing data on visit results for 3 households (Table 2).

During the first weeks of recruitment and field work (October 29 through November 26), we had a response rate of 20%. To improve response rates, and as required by the Healthy Wells project description, we placed a Healthy Wells advertisement in the Gaston Gazette on Monday, November 27, 2017. On December 3, 2017 we implemented a shorter recruiting script which contained simpler language. We also removed the option for residents to complete the survey themselves using the Mesa II tablets because we thought that the offer may have imposed a technological barrier on many potential respondents. Instead, we required the interviewers to administer the survey verbally. Response rates decreased slightly to 19% after placing the newspaper advertisement, implementing a new recruiting script, and implementing the new survey administration procedure (December 3, 2017 through January 14, 2018).

In a continued effort to improve response rates, on January 16, 2018 interviewers started to distribute Healthy Wells flyers to the houses that we would be vising in the coming weekends. We designed the flyers to give the residents notice that we would be asking to test their well water, administer a survey, and collect well coordinates within the following two weeks. Response rates between January 21, 2018 and February 25, 2018 increased to 26%. The changes in response rates between October 29, 2017 and February 25, 2018 were not statistically significant ($\chi^2 = 16.1525, p = 0.095$).

Of the households that we visited or attempted to visit, 567 are in low socioeconomic status census tracts (between 67.4% and 78.4% of residents ages 25 and older are high school graduates or higher), 533 in medium socioeconomic status census tracts (between 78.5% and 84.4% high school graduates or higher), and 796 in high socioeconomic status census tracts (between 84.5% and 92.1% high school graduates or higher) (Figure 3).

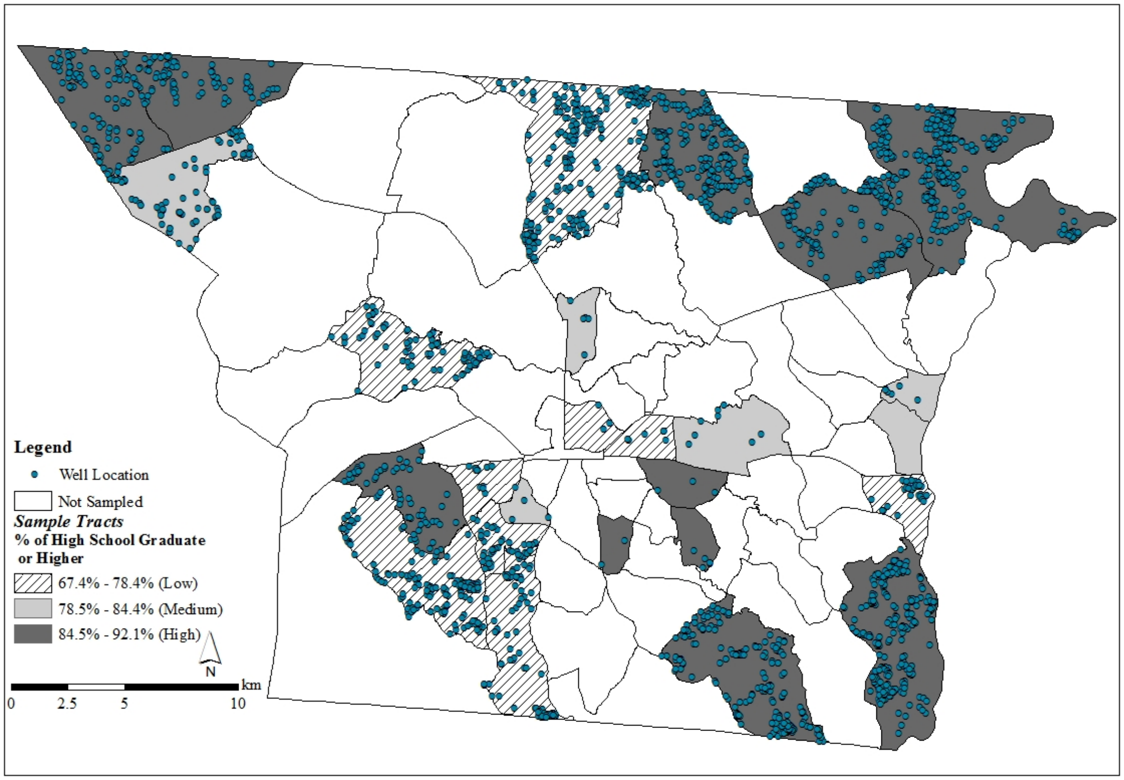

Figure 3. Map of sample population in Gaston County, North Carolina (attempted and successful visits)

The low and medium socioeconomic status census tracts had response rates of 22%, and the high socioeconomic status census tracts had a response rate of 20%. The differences in response rates between socioeconomic status groups was not statistically significant ($\chi^2 = 0.4158; p = 0.812$).

5.2 Household characteristics

Of the 138 households that participated in this study, 49 have at least one individual under the age of 18 living in the residence, and 43 have at least one individual ages 65 or older living in the residence (Table 3).

Table 3.

Household characteristics of sample in Gaston County, North Carolina

Variable	n	% of sample
At least 1 individual under 18 years of age living in the residence		
Yes	49	35
No	85	62
Prefer not to respond	3	2
Missing	1	1
At least 1 individual ages 65 or older living in the residence		
Yes	43	31
No	91	66
Prefer not to respond	2	1
Missing	2	2
Race		
Mixed race	6	4
White	107	78
Black or African American	4	3
American Indian and Alaska Native	1	1
Asian	1	1
Native Hawaiian and Other Pacific Islander	0	0
Some other race	3	2
Prefer not to respond	10	7
Missing	6	4
Ethnicity		
Hispanic or Latino	2	1
Not Hispanic or Latino	107	78
Prefer not to respond	20	14
Missing	9	7
Highest level of education		
Less than high school	12	9
High school graduate or equivalency	9	6
Some college or associate's degree	7	5
Bachelor degree or equivalency	12	9
Higher than a Bachelor degree	9	6
Prefer not to respond	22	16

Missing	67	49
Income		
Less than $10,000	1	1
$10,000 to $14,999	1	1
$15,000 to $24,999	2	1
$25,000 to $34,999	8	6
$35,000 to $49,999	4	3
$50,000 to $74,999	22	16
$75,000 to $99,999	15	11
$100,000 to $149,999	18	13
$150,000 to $199,999	5	3
$200,000 or more	1	1
Prefer not to respond	47	34
Missing	14	10
Length of time lived in the home		
0-1 years	6	4
2-3 years	10	7
4-5 years	4	3
6-7 years	0	0
8-9 years	1	1
10 years or more	40	29
Prefer not to respond	6	4
Missing	71	52
Home ownership		
Owned	120	87
Rented	8	6
Missing	10	7

There is little racial or ethnic diversity in the obtained sample: 78% of the households are of white race (*n=107, 78%*), followed by mixed race (*n=6, 4%*) and Black or African American (*n=4, 3%*), and most of the households are not Hispanic or Latino (*n=107, 78%*). The majority of households did not provide data about the highest level of education in the household (*n=89, 65%*). Of those that did provide educational attainment data, twelve have less than a high school education, twelve have a Bachelor degree or equivalency, nine have a high school diploma or equivalency, and nine have higher than a Bachelor degree (Table 3). Many households also refused to provide information about annual household income (*n=61, 44%*). Twenty-two households reported earning between $50,000-$74,999 annually, 18 reported earning between $100,000-$149,999 annually, and 15 reported earning $75,000-$99,999 annually. Data on length of time lived in the home is missing for over half of the respondents, and 40 households reported having lived in the residence for ten years or more. Most respondents (*n=120*) reported owning their residence (Table 3).

5.3 Household characteristic and pathogenic well water contamination

We tested water samples for the presence of total coliform and *E. coli*. Thirty-seven (27%) wells tested positive for total coliform, while two (1%) wells tested positive for *E. coli* (Table 4) (Figure 4).

Table 4.

Well water test results from sample in Gaston County, North Carolina

Variable	n	% of sample
Total coliform test results		
Positive	37	27
Negative	101	73
E. coli test results		
Positive	2	1
Negative	136	99

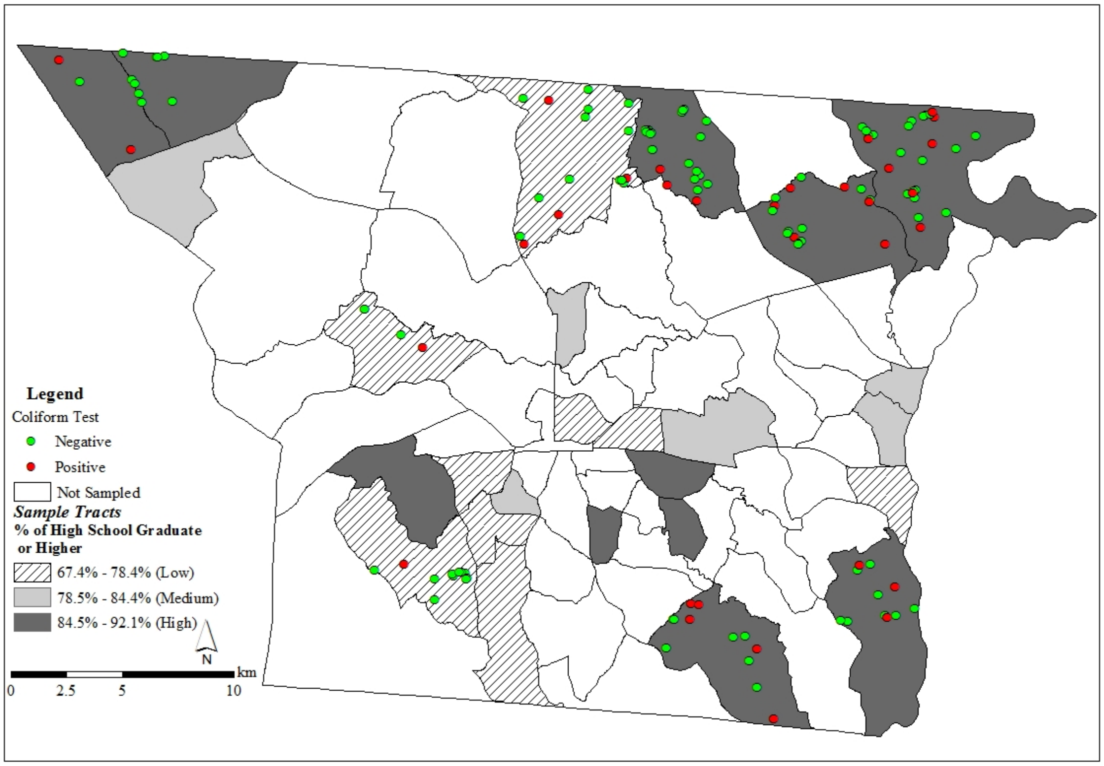

Figure 4. Map of total coliform test results in Gaston County, NC

Despite acquiring a sample size that was not large enough to reach the desired level of power and statistical significance, I conducted chi-2 (χ^2) tests between the independent variables and total coliform well water test results. None of the relationships between the independent variables and total coliform results were statistically significant at the alpha (α) level of 0.05 (Table 5). Since I did not find any relationships that were statistically significant, I did not conduct a logistic regression.

Table 5.

Household characteristics and total coliform test results of sample in Gaston County, North Carolina

Independent variable	Positive for total coliform	$\chi 2$	Probability
At least one individual under the age of 18 in the residence		0.1144	0.735
Yes	14		
No	22		
At least one individual over the age of 65 in the residence		2.0718	0.150
Yes	15		
No	21		
Race		8.3358	0.139
Mixed race	3		
White	26		
Black or African American	2		
American Indian and Alaska Native	0		
Asian	1		
Native Hawaiian and Other Pacific Islander	0		
Some other race	2		
Ethnicity		0.6308	0.427
Hispanic or Latino	2		
Missing data	27		
Highest level of education in the household		3.8774	0.423
Less than high school	1		
High school graduate or equivalency	3		
Some college or associate's degree	1		
Bachelor degree or equivalency	4		
Higher than a Bachelor degree	1		
Annual household income		9.0965	0.428
Less than $10,000	0		
$10,000 to $14,999	0		
$15,000 to $24,999	0		
$25,000 to $34,999	3		
$35,000 to $49,999	1		
$50,000 to $74,999	9		
$75,000 to $99,999	4		
$100,000 to $149,999	1		
$150,000 to $199,999	1		
$200,000 or more	0		

Length of time lived in the home		3.8368	0.429
0-1 years	3		
2-3 years	2		
4-5 years	0		
6-7 years	-----		
8-9 years	0		
10 years or more	10		
Home ownership		0.0634	0.801
Owned	35		
Rented	2		

CHAPTER 6: DISCUSSION

The aim of the current study was to examine the relationship between the household characteristics of private well users and pathogenic contamination of private wells in Gaston County, North Carolina. After measuring bacterial well water quality (total coliform) and household characteristics (at least on individual under the age of 18 in the household; at least one individual ages 65 and older in the household; race; ethnicity; annual household income; highest level of educational in the household; homeownership; and, length of time living in the house), I analyzed the relationship between the variables of interest using a series of chi-2 (χ^2) tests.

Although my sample size was too small to reach a significance level (α) of 0.05 and a power level (β) of 0.95, the relationships between household characteristics and pathogenic contamination of private wells was not adequately strong to be useful for application within the local setting. Even if I found statistically significant patterns with a larger sample size, any relationship would be inadequate to be meaningful to a private well outreach program for the Gaston County Department of Health and Human Services- Environmental Health.

The rate of total coliform contamination in Gaston County is consistent with rates previously found in the literature (between 23-78%) (Allevi et al., 2013; Borchardt et al., 2003; DiSimone et al.; Fong et al., 2007; Gonzales, 2008). The rate of *E. coli* contamination in Gaston County (1%) is slightly lower than the rates estimated in the literature (between 2-10%) (Allevi et al., 2013; Borchardt et al., 2003; DiSimone et al.; Fong et al., 2007; Gonzales, 2008).

Private wells in Gaston County appear to be more likely to be contaminated than municipal water. In 2016, Two Rivers Utilities— serving approximately 10,000 residents in Gaston County— had zero total coliform violations (Two Rivers Utilities, 2016). A limitation of the comparison between Two River Utilities and private wells in Gaston County is that municipal water is required to test positive for total coliform in two consecutive samples to be considered a violation, and we did not re-test all wells that tested positive for total coliform in our sample. Nonetheless, Gaston County private well users may be at a higher risk of exposure to pathogenically contaminated well water than public water users. The increased risk of exposure is consistent with literature showing that private well water in Wake County, North Carolina was more likely to contain bacterial contaminants than public water (Stillo et al., 2017) and that private water is more likely to be contaminated than public water (DeFelice et al., 2016; Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., Snipes, M. , 2011; Heaney, C.D. et al., 2013; Stillo et al., 2017). Exposure to pathogenically-contaminated drinking water presents a health concern due to the potential for causing water-borne illness.

The response rate for the current study was 21%, and the overall survey response rate for Healthy Wells during the recruitment period for the current study was 22%. These response rates are lower than response rates in similar studies, although recruitment methods differed slightly. Heaney et al. (2011) attained a response rate of 48% in door-to-door recruitment. However, recruiters were trained community members who lived in the neighborhoods in which they recruited. Dodge & Chapman (2018) attained a response rate of 38%, but the research team made four attempts at contact at each potential household. Casey et al. (2018) used six recruitment methods to enroll households in a Healthy Homes program, and door-to-door neighborhood canvassing accounted for 15% of enrollment, behind person-to-person referrals (46%) and direct mail (23%).

6.1 Strengths and limitations

The strengths of the current study are the sampling method used, the protocol employed to implement the study, and the partnership between the University of North Carolina at Charlotte and Gaston County Department of Health and Human Services-Environmental Health. The stratified random sampling method increased the likelihood that our sample would contain households of multiple socioeconomic levels. I developed a strict protocol for study implementation to minimize systematic error, such as interviewer error or bias. To further minimize interviewer bias in recruiting, I rotated interviewers through census tracts with different socioeconomic levels each weekend. The recruitment script from the protocol contained simple, clear language so that it was accessible to potential respondents. I minimized affinity bias in the recruitment protocol by giving interviewers lists of houses which were ordered based on geographic location. Interviewers were instructed to visited households in the most efficient geographic order. We offered Gaston County private well users free well testing as an incentive for their participation in the project. The partnership between the University of North Carolina at Charlotte and the Gaston County Department of Health and Human Services-Environmental Health allowed us to maximize the wealth of knowledge and resources inherent to an interdisciplinary team.

Despite the strengths of the stratified random sampling method, the method also has its limitations. The order in which interviewers visited homes within the census tracts may have been a source of bias. The recruitment protocol may have introduced limitations because interviewers only recruited and completed field work on Sundays, limiting potential respondents to those who are at home and available on Sundays.

The current study was a cross-sectional study, limiting my ability to infer relationships between variables of interest. There may be variables which confound or moderate the relationship between household characteristics and well water contamination. For example, I did not evaluate how risk perception may influence environmental stewardship and water quality outcomes. The household characteristics variables I measured are closely related and may confound one another.

Some private well users may have been excluded due to the recruiting and study protocols or inclusion criteria. The Household Characteristics Survey was only offered in English, so non-English speakers were unable to participate in the study. Some renters may have been excluded if they were unable to consent to well water testing. Other barriers to participation may have been the low persistence of contact by visiting each household only once; low public knowledge of the Healthy Wells project; and, the nature of the request in that respondents had to answer survey questions administered face-to-face by a stranger. Although we attempted to spread knowledge of the project among Gaston County well users using a newspaper advertisement, the advertisement was published on a Monday. Therefore, the reach of the audience who viewed the advertisement may have been limited.

During survey administration, we had a high rate of item non-response. Approximately 64% of respondents selected “prefer not to respond” or did not respond to the question about highest level of educational attainment in the household, 44% of respondents selected “prefer not to respond” or did not respond to the question about the annual household income, and 56% of respondents selected “prefer not to respond” or did not respond to the question about length of time lived in the home. Item nonresponse may have been attributable to the survey design. The demographic questions appeared at the end of the Healthy Wells survey, following twenty questions that were administered for the purposes of the Gaston County Department of Health and Human Services-Environmental Health. Due to the length of the survey, respondents may have experienced fatigue by the time they reached the demographic questions. The order of the questions in the survey may have also attributed to high item nonresponse.

Question design may have also influenced item nonresponse. The questions, originally written to be administered using a self-paced electronic survey, may have been difficult to comprehend when administered verbally. In particular, the item about educational attainment may have been difficult to understand because we asked for total years of educational attainment, rather than a categorical response. Ten respondents reported the highest level of educational attainment in the household was between two to four years, but these respondents may have intended to report two to four years of education beyond twelfth grade. Nonetheless, I coded the variables as reported. When I conducted the analysis of the association between well water test results and education with the variables recoded as twelve years plus the number of years reported by the respondent, the results were not statistically significant (Table 6).

Table 6.

Household characteristics and total coliform test results with educational attainment assumption

Independent variable	Positive for total coliform	$\chi 2$	Probability
Highest level of education in the household		1.6640	0.797
Less than high school	0		
High school graduate or equivalency	3		
Some college or associate's degree	1		
Bachelor degree or equivalency	4		
Higher than a Bachelor degree	2		

I also obtained a high unit nonresponse, with only 21% of respondents agreeing to participate in the study. The demographic homogeneity of Gaston County indicates that the survey language should not have been a major factor in response rates. Potential respondents reported having already tested their well, not being able to consent to testing because they are renters, not wanting to test because they filter their water, a lack of trust in the authenticity of the project, and a perception of having "good water". Interviewers attempted to build trust with potential respondents by giving the respondents official Gaston County business cards for the project coordinator; by wearing Gaston County Department of Health and Human Services hats; and, by offering to call the project coordinator if the respondent had any questions about the project.

The method we used for recruiting may have introduced bias into the study. Interviewers visited each house once unless potential participants called us to return. While the well users who requested our return (n=10) were likely different in some way than those who did not, a source of possible self-selection bias, this difference was not of concern in the current study due to the lack of significant findings. We faced accessibility bias since we were unable to access some homes due to road conditions, construction, or inability to locate the property. Interviewers did not enter properties which had “No Trespassing” or “Private Property” signs posted, and they could choose not to visit homes which made them uncomfortable or unsafe, such as those with off-leash dogs in the yard. The residents who live in homes with signs posted, or homes which the interviewers chose not to visit, may be systematically different than the residents we visited.

6.2 Recommendations

I found that that all private well users in Gaston County, compared to public water users, are at a relatively high risk of exposure to pathogenically-contaminated water. Based on the data collected thus far, I did not find evidence of sociodemographic disparities in access to safe drinking water among private well users in Gaston County. The prioritization of private well interventions toward sociodemographic sub-groups in Gaston County would, therefore, be an inefficient use of county resources. Instead, the Gaston County Department of Health and Human Services- Environmental Health might consider different ways to prioritize private well interventions.

The Gaston County Department of Health and Human Services-Environmental Health might consider focusing its private well efforts on specific geographic areas which have higher rates of pathogenic private well water contamination (Figure 4). One goal of the Healthy Wells project is to provide a spatial picture of well water contamination in Gaston County using geographic information systems. As spatial data on pathogenic groundwater contamination become available over the course of the project, the Healthy Wells team will be able to systematically discern any geographic patterns of contamination that may exist. In the future, spatial groundwater contamination patterns might inform private well interventions and programming by the Gaston County Department of Health and Human Services- Environmental Health.

Another goal of the Healthy Wells project is to determine barriers to and motivations for well testing and maintenance behaviors among private well users in Gaston County. As the project continues, and more private well users complete Healthy Wells survey questions regarding well testing behaviors, the Gaston County Department of Health and Human Services might use the data collected to further inform private well programming priorities. Furthermore, the Gaston County Department of Health and Human Services- Environmental Health will be able to discern whether well testing behaviors of private well users changed after learning about their well water quality and receiving risk communication materials, information which will help environmental health professionals understand which interventions successfully lead to behavior change among private well users.

An expansion of the Healthy Wells project may consider analyzing chemical contamination of private wells. Groundwater may become contaminated by inorganic chemicals, such as nitrate or heavy metals, or organic substances, such as pesticides, from local and non-local sources (NC Department of Environmental Quality, 2018). Concerns about coal ash contamination of groundwater in Gaston County warrants further investigation into the prevalence of coal ash contamination of private wells (NC Department of Environmental Quality, 2018).

A barrier that we continue to face with the implementation of the Healthy Wells project is resistance among the population of private well users to assistance from the health department, as well as a lack of trust among private well users of the research and environmental health communities. Education about the health risk of contaminated drinking water is important since a lack of knowledge is one of the primary barriers to behavior change (Morris, Wilson, & Kelly, 2016). Therefore, educational outreach to private well users is a key step in motivating well users to test their well water regularly for contamination. I recommend that the Gaston County Department of Health and Human Services continues to explore methods to build trust among the population of private well users, such as by promoting the project through trusted community leaders and organizations, to facilitate better communication with private well users about the health risks of drinking contaminated water.

REFERENCES

Private drinking water well sampling, 15A-NCAC-18A C.F.R. § 3801-3805 (2008)

Aiken, Charles S. (1987). Race as a factor in municipal underbounding. *Annals of the Association of American Geographers, 77*(4), 564-579. doi:10.1111/j.1467-8306.1987.tb00181.x

Allevi, R. P., Krometis, L. A., Hagedorn, C., Benham, B., Lawrence, A. H., Ling, E. J., & Ziegler, P. E. (2013). Quantitative analysis of microbial contamination in private drinking water supply systems. *J Water Health, 11*(2), 244-255. doi:10.2166/wh.2013.152

Balazs, C.L., & Ray, I. (2014). The drinking water disparities framework: On the origins and persistence of inequities in exposure. *Am J Public Health, 204*(4), 603-611. doi:10.2105/AJPH.2013.301664

Beer, K.D., Gargano, J.W., Roberts, V.A., Hill, V.R., Garrison, L.E., Kutty, P.K., . . . Yoder, J.S. (2015). Surveillance for waterborne disease outbreaks associated with drinking water— United States, 2011-2012. *Morbidity and Mortality Weekly Report, 64*(31), 842-848

Bellinger, D.C. (2016). Lead contamination in Flint— An abject failure to protect public health. *The New England Journal of Medicine, 374*(12), 1101-1103. doi:10.1056/NEJMp1601013

Borchardt, M. A., Bertz, P. D., Spencer, S. K., & Battigelli, D. A. (2003). Incidence of enteric viruses in groundwater from household wells in Wisconsin. *Applied and Environmental Microbiology, 69*(2), 1172-1180. doi:10.1128/aem.69.2.1172-1180.2003

Calderon, R.L., Johnson Jr., C.C., Craun, G.F., DuFour, A.P., Karlin, R.J., Sings, T., & Valentine, J.L. (1993). Health risks from contaminated water: Do class and race matter? *Toxicology and Industrial Health, 9*(5), 879-900. doi:10.1177/074823379300900510

Campbell, C., Greenberg, R., Mankikar, D., & Ross, R. D. . (2016). A case study of environmental injustice: The failure in Flint. International Journal of Environmental Research and Public Health, 13(10), 951. doi:10.3390/ijerph13100951

Center for Disease Control and Prevention. (2010). Well testing. Retrieved 4 September 2017 from https://www.cdc.gov/healthywater/drinking/private/wells/testing.html

Centers for Disease Control and Prevention. (2009). Well siting & potential contaminants. Retrieved 15 August 2017 from https://www.cdc.gov/healthywater/drinking/private/wells/location.html

Centers for Disease Control and Prevention. (2010). Well testing. Retrieved 2 August 2017 from https://www.cdc.gov/healthywater/drinking/private/wells/testing.html

Centers for Disease Control and Prevention. (2014). Public water systems. Retrieved 2 September 2017 from https://www.cdc.gov/healthywater/drinking/public/index.html

Centers for Disease Control and Prevention. (2015). Overview of water-related diseases and contaminants in private wells. Retrieved 2 September 2017 from https://www.cdc.gov/healthywater/drinking/private/wells/index.html

Centers for Disease Control and Prevention. (2016). Water & nutrition. Retrieved 24 July 2017 from https://www.cdc.gov/healthywater/drinking/nutrition/index.html

Craun, G., Craun, M., Heberling, M.T., Murphy, P.A., Rice, G.E., Rothermich, M.M., & Wright, J.M. (2007). *Estimating the burden of disease associated with outbreaks reported to the U.S. waterborne disease outbreak surveillance system: Identifying limitations and improvements*. (EPA/600/R-06/069). Cincinnati, OH: Office of Research and Development.

DeFelice, N.B., Johnston, J.E., & MacDonald Gibson, J. (2016). Reducing emergency department visits for acute gastrointestinal illnesses in North Carolina (USA) by extending community water service. *Envrionmental Health Perspectives, 124*(10), 1583-1591. doi:0.1289/EHP16010.1289/EHP160

DiSimone, L.A., Hamilton, P.A., & Gilliom, R.J. (2009). *Quality of water from domestic wells in principle aquifers of the United States, 1991-2004*. Reston, Virginia: US Geological Survey

Division of Enviromental Public Health. (2016). *Coliform bacteria and drinking water*. (331-181). Retrieved 24 July 2017 from http://www.doh.wa.gov/Portals/1/Documents/Pubs/331-181.pdf

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavioral Research Methods, 41*(4), 1149-1160. doi:10.3758/BRM.41.4.1149

Faul, F., Erdfelder, E., Lang, A.G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavioral Research Methods, 39*(2), 175-191. doi:10.3758/BF03193146

Flanagan, S. V., Marvinney, R. G., & Zheng, Y. (2015). Influences on domestic well water testing behavior in a central Maine area with frequent groundwater arsenic occurrence. Sci Total Environ, 505, 1274-1281. doi:10.1016/j.scitotenv.2014.05.017

Fong, T. T., Mansfield, L. S., Wilson, D. L., Schwab, D. J., Molloy, S. L., & Rose, J. B. (2007). Massive microbiological groundwater contamination associated with a waterborne outbreak in Lake Erie, South Bass Island, Ohio. *Environ Health Perspect, 115*(6), 856-864. doi:10.1289/ehp.9430

Fox, M. A., Nachman, K. E., Anderson, B., Lam, J., & Resnick, B. (2016). Meeting the public health challenge of protecting private wells: Proceedings and recommendations from an expert panel workshop. *Sci Total Environ, 554-555*, 113-118. doi:10.1016/j.scitotenv.2016.02.128

Gonzales, T.R. (2008). The effects that well depth and wellhead protection have on bacterial contamination of private water wells in the Estes Park Valley, Colorado. *Journal of Environmental Health, 71*(5), 17-23.

Greenberg, M. R. (2016). Delivering fresh water: Critical infrastructure, environmental justice, and Flint, Michigan. *Am J Public Health, 106*(8), 1358-1360. doi:10.2105/AJPH.2016.303235

Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., & Snipes, M. . (2011). Use of community-owned and -managed research to assess the vulnerability of water and sewer services in marginalized and underserved environmental justice communities. *J Environ Health, 74*(1), 8-17. doi:10.2105/AJPH.2016.303235

Heaney, C., Wilson, S., Wilson, O., Cooper, J., Bumpass, N., Snipes, M… (2011). Use of community-owned and -managed research to assess the vulnerability of water and sewer services in marginalized and underserved environmental justice communities. J Environ Health, 74(1), 8-17.

Heaney, C.D., Wing, S., Wilson, S.M., Campbell, R.L., Caldwell, D., Hopkins, B., … Yeatts, K. (2013). Public infrastructure disparities and the microbiological and chemical safety of drinking and surface water supplies in a community bordering a landfill. *J Environ Health, 75*(10), 24-36.

Johnson, J.H., Parnell, A., Joyner, A.M., Christman, C.L., & Marsh, B. (2004). Racial apartheid in a small North Carolina town. *The Review of Black Political Economy*, 31(4), 89–107. doi:10.1007/s12114-004-1012-4

Jones, A. Q., Dewey, C. E., Dore, K., Majowicz, S. E., McEwen, S. A., Waltner-Toews, D., … Mathews, E. (2005). Public perception of drinking water from private water supplies: Focus group analyses. *BMC Public Health, 5*, 129. doi:10.1186/1471-2458-5-129

Kreutzwiser, R., de Loe, R., Imgrund, K., Conboy, M. J., Simpson, H., & Plummer, R. (2011). Understanding stewardship behaviour: Factors facilitating and constraining private water well stewardship. *J Environ Manage, 92*(4), 1104-1114. doi:10.1016/j.jenvman.2010.11.017

Licther, D.T., Parisi, D., Grice, S.M., & Taquino, M. (2007). Municipal underbounding: Annexation and racial exclusion in small Southern towns. *Rural Sociology, 72*(1), 47-68. doi:10.1526/003601107781147437

MacDonald Gibson, Jacqueline, DeFelice, Nicholas, Sebastian, Daniel, & Leker, Hannah. (2014). Racial disparities in access to community water supply service in Wake County, North Carolina. *American Journal of Public Health, 104*(12), e45-e45. doi:10.2105/AJPH.2014.10412e45.1

Macintyre, S., Ellaway, A., & Cummins, S. (2002). Place effects on health: How can we conceptualise, operationalise and measure them? *Social Science and Medicine, 55*(1), 125-139. doi:10.1016/S0277-9536(01)00214-3

Malecki, K. M. C., Schultz, A. A., Severtson, D. J., Anderson, H. A., & VanDerslice, J. A. (2017). Private-well stewardship among a general population based sample of private well-owners. *Sci Total Environ, 601-602*, 1533-1543. doi:10.1016/j.scitotenv.2017.05.284

Morello-Frosch, R. (2002). Discrimination and the political economy of environmental inequality. *Environment and Planning C: Government and Policy, 20*(4), 477-496. doi:10.1068/c03r

Morris, L., Wilson, S., & Kelly, W. (2016). Methods of conducting effective outreach to private well owners— A literature review and model approach. *Journal of Water and Health, 14*(2), 167-182. doi:10.2166/wh.2015.081

Naman, J.M.N., & MacDonald Gibson, J. (2016). Disparities in water and sewer services in North Carolina: An analysis of the decision-making process. *Am J Public Health*. doi:10.2105/AJPH.2015.302731

NC Department of Environmental Quality. (2018). Coal ash docs. Retrieved 4 July 2017 from https://deq.nc.gov/about/divisions/water-resources/water-resources-permits/wastewater-branch/npdes-wastewater/coal-ash-docs

NC Department of Health and Human Services. (2016). NC DPH Epidemiology: Well water and health. Retrieved 26 July 2017 from http://epi.publichealth.nc.gov/oee/wellwater/figures.html

Patel, A. I., & Schmidt, L. A. (2017). Water access in the United States: Health disparities abound and solutions are urgently needed. *Am J Public Health, 107*(9), 1354-1356. doi:10.2105/AJPH.2017.303972

Popkin, B. M., D'Anci, K. E., & Rosenberg, I. H. (2010). Water, hydration, and health. *Nutrition Reviews, 68*(8), 439-458. doi:10.1111/j.1753-4887.2010.00304.x

Rogan, W. J., Brady, M. T., Committee on Environmental Health, & Committee on Infectious Diseases. (2009). Drinking water from private wells and risks to children. *Pediatrics, 123*(6), e1123-1137. doi:10.1542/peds.2009-0752

Shavers, V.L. (2007). Measurement of socioeconomic status in health disparities research. *Journal of the National Medical Association, 99*(9), 1013-1023.

Stillo, F., & MacDonald Gibson, J. (2017). Exposure to contaminated drinking water and health disparities in North Carolina. *Am J Public Health, 101*(1), 180-185. doi:10.2105/

Switzer, David, & Teodoro, Manuel P. (2017). Class, race, ethnicity, and justice in safe drinking water compliance. *Social Science Quarterly*. doi:10.1111/ssqu.12397

Two Rivers Utilities. (2016). *2016 Annual Water Quality Report* (01-36-010). Retrieved from https://www.cityofgastonia.com/water-services/water-confidence-report-2016.html

US Census Bureau. (2008). *American Housing Survey for the United States: 2007*. Washington D.C.: US Government Printing Office.

US Census Bureau. (2014). Census explorer. Retrieved 24 July 2017 from https://www.census.gov/censusexplorer/

US Census Bureau. (2017). U.S. Census Bureau Quickfacts selected: Lincoln County, North Carolina; Mecklenburg County, North Carolina; North Carolina; Gaston County, North Carolina. Retrieved 24 July 2017 from https://www.census.gov/quickfacts/fact/table/lincolncountynorthcarolina,mecklenburgcountynorthcarolina,NC,gastoncountynorthcarolina/PST045216

US Environmental Protection Agency. (2013). *Revised total coliform rule: A quick reference guide*. Retrieved 4 September 2017 from https://www.gslabs.com/Revised Total Coliform Rule.pdf

US Environmental Protection Agency. (2016). About private water wells. Retrieved 24 July 2017 from https://www.epa.gov/privatewells/about-private-water-wells

US Environmental Protection Agency. (2017a). EJ 2020 Action Agenda: EPA's environmental justice strategy. Retrieved 4 September 2017 from https://www.epa.gov/environmentaljustice/ej-2020-action-agenda-epas-environmental-justice-strategy

US Environmental Protection Agency. (2017b). Environmental justice. Retrieved 24 July 2017 from https://www.epa.gov/environmentaljustice

US Environmental Protection Agency. (2017c). Human health and contaminated water. Retrieved 14 July 2017 from https://www.epa.gov/privatewells/human-health-and-contaminated-water

US Environmental Protection Agency. (2017d). National primary drinking water regulations. Retrieved 14 July 2017 from https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

US Environmental Protection Agency. (2017e, 2018-01-12). Safe Drinking Water Act (SDWA). Retrieved 16 July 2017 from https://www.epa.gov/sdwa

VanDerslice, J. (2011). Drinking water infrastructure and environmental disparities: Envidence and methodological considerations. *Am J Public Health, 101*(S1), S109-S114. doi:10.2105/

Washington State Department of Agriculture, Washington State Department of Ecology, Washington State Department of Health, Yakima County Public Works Department, & US Environmental Protection Agency. (2010). *Lower Yakima Valley groundwater quality: Preliminary assessment and recommendations document*. Retrieved 15 July 2017 from https://fortress.wa.gov/ecy/publications/publications/1010009.pdf

Wilson, Sacoby M. (2009). An ecologic framework to study and address environmental justice and community health issues. *Environmental Justice, 2*(1), 15-24. doi:10.1089/env.2008.0515

Wilson, Sacoby M., Heaney, Christopher D., Cooper, John, & Wilson, Omega. (2008). Built environment issues in unserved and underserved African-American neighborhoods in North Carolina. *Environmental Justice, 1*(2), 63-72. doi:10.1089/env.2008.0509

APPENDIX A: HOUSEHOLD CHARACTERISTICS SURVEY

*Well Permit ID: ____________

*Result of visit:
1. Home and consented
2. Home but denied consent
3. Not home

Household Characteristics Survey

Now that we know more about your well and well water, we would like to ask for some information about your household. This will help us learn about what kinds of things might best help the community using wells.

1. Is there at least one member of the household under the age of 18??
    a. Yes
    b. No
    c. Prefer not to respond

2. Is there at least one member of the household who is age 65 or older?
    a. Yes
    b. No
    c. Prefer not to respond

3. Would you characterize the household as:
    a. Mixed race
    b. White
    c. Black or African American
    d. American Indian and Alaska Native
    e. Asian
    f. Native Hawaiian and Other Pacific Islander
    g. Some other race (fill in the blank)____________
    h. Prefer not to respond

4. Would you characterize the household as:
    a. Hispanic or Latino
    b. Not Hispanic or Latino
    c. Prefer not to respond

5. What is the highest level of education that has been completed in the household?
    a. ____Years
    b. Prefer not to respond

6. What is the annual household income?
    a. Less than $10,000
    b. $10,000 to $14,999
    c. $15,000 to $24,999
    d. $25,000 to $34,999
    e. $35,000 to $49,999
    f. $50,000 to $74,999
    g. $75,000 to $99,999
    h. $100,000 to $149,999
    i. $150,000 to $199,999
    j. $200,000 or more
    k. Prefer not to respond

7. How long have you lived in this house?
    a. _______ Years
    b. Prefer not to respond

8. Is the house owned or rented by residents?
    a. Owned
    b. Rented

Thank you!

9. *What type of assistance was provided by the interviewer?
    a. Technical
    b. Verbal survey completion
    c. None

*To be completed by the interviewer.

APPENDIX B: RECRUITING SCRIPT

Good (morning/afternoon),

We're working for Gaston County Environmental Health on a project to help make sure everyone in Gaston County has safe drinking water. We would like to test your well for bacterial contamination for free. The results will be mailed to you within 1 to 2 weeks, and they will tell you whether your water potentially contains harmful bacteria. Here is a brochure from the County that is part of this program. Would you like to participate?

(If they say yes, proceed.)

Great. We are also collecting photographs and coordinates of wells. This will help monitor groundwater quality throughout the county. Is that okay too?

(Whether they say yes or no, proceed to offer survey).

Great. Before we begin, we would like to ask you a few questions. It should take just a few minutes and provide important information about the use of wells in the county. The results also will help a graduate student at UNC Charlotte who is comparing information about people who use wells to the quality of their water. Are you alright with responding to these questions and your answers being used for this work?

(If they say yes, proceed)

Are you at least 18 years of age? Is this household your primary residence?

(If they answer yes to both questions, mark that they consented.)

In case you have any questions or concerns, this form includes more information about the study, as well as her contact information.

(Give participant the information sheet.)

(Proceed with survey.)