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Land Use Planning, Policy, and Water Quality Nexus for *Escherichia coli* Mitigation: A Case Study of Greenville, SC

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LAND USE PLANNING, POLICY, AND WATER QUALITY NEXUS FOR *Escherichia coli* MITIGATION: A CASE STUDY OF GREENVILLE, SC

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ABSTRACT

Pathogenic impairments are widespread across the United States and the source of the pollutant is both complicated and often elusive. The boundary of Greenville County, South Carolina crosses four Hydrologic Unit Code 8 watershed designations, and within those, there are over one hundred approved Total Maximum Daily Loads related to fecal indicator bacteria. This region is experiencing rapid growth and development; consequently, it is critical for planners to better understand the nexus between land use choices and water quality impacts, as zoning, ordinance decisions, and comprehensive plans can affect this relationship. The goal of this research was to correlate urbanized land cover from the National Land Cover Database and land uses by examining impervious surface types with *E. coli* levels in Greenville County and from those results, provide insight for land use planning policy. I hypothesized that there was a relationship between land cover typology and impervious land uses with *E. coli*, which could generate land management policy adjustments. The null hypothesis was that no correlation could be determined between land cover or land use and *E. coli* levels in Greenville County. The analysis revealed the following results, rejecting the null hypothesis. First, both developed land cover and land use types lead to increases in *E. coli* levels. Second, the presence of National Pollutant Discharge Elimination System permits and agricultural fecal spreading permits lead to decreases in *E. coli*. Third, and most importantly, knowledge of the sampling condition, specifically wet weather, is highly correlated to *E. coli* levels and leads to significant increases in measured *E. coli*. This third observation indicates that land use, the presence of sewer overflows, failing septic tanks, the

resuspension of bottom sediment living *E. coli*, or a combination of these appears to elevate *E. coli* levels. Despite the presence of this relationship, the resulting adjusted coefficients of determination (R^2) from both multi linear regression analysis (0.41-0.42) and factor analysis (0.21) suggest that there are sources of *E. coli* for which this study does not account. Accordingly, it will be essential to conduct additional research that examines the relationship between more accurately-specified land use types and *E. coli* levels. Also, there is a need to understand the nuances of the relationship between wet weather sampling conditions and *E. coli* presence and concentration fluctuation. Regardless of the remaining gaps, this research reinforces the imperative involvement of planners in conversations about water quality within their jurisdictions. The consequences of land use policy making are evident in water quality, and planners should be cognizant of water quality consequences as they accommodate and plan for future urban growth.

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I would like to recognize the help of family both near and far for their support and for providing me much needed mental breaks. I am thankful to be so loved.

Finally, I would like to thank my City and Regional Planning family, whom have provided comic relief, a listening ear, and genuine support for the past two years. I look forward to watching them grow and succeed in their planning careers.

DEDICATION

I dedicate this thesis to all of the planners who keep both human and environmental needs at the forefront of their decisions. May we all continue to be conscientious of the effects that our leadership advice and choices have on the health of our ecosystem. And may we continue to bridge the communication gap across both public and private sectors as we work towards cleaner water.

Reedy River Waterfalls

Gentle they are, as lace their waters going
Over primeval bed of stone in lullaby.
Sweet as the rippling music softly flowing
In lonely church to one who enters passing by:
Ceaseless and changeless, yet forever changing,
Murmuring, gurgling, tinkling, counter-ranging.

Happy the City in whose heart forever running
Music so linked with loveliness of view!
Not roar of cataract, its thunders stunning:
Tater the lulling harmony Pan's piping blew
When earth was young and through the pristine day
Clear waters silvery flowing banished care away

— Robert Adger Bowen, 1969

Poem found in The Story of Reedy River (McKoy, 1969). Although beloved and lauded for its beauty at the time, the Reedy River was heavily polluted. Since the passing of the Clean Water Act in 1972, the health of the river, along with many other urban water systems across the United States, has come a long way. But there is more work to be done. We must continue to strive for better care of our most precious resource, clean water, and push the envelope for better policy for both land use and water planning.

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LIST OF ACRONYMS

AIC	Akaike's Information Criterion
AM	Adaptive Management
APA	American Planning Association
ArcGIS	Software mapping tool for Geographic Information System
BAT	Best Available Technology
BIC	Bayesian Information Criterion
BMP	Best Management Practice
BPT	Best Practicable Control
CAA	Clean Air Act
CAFO	Concentrated Animal Feeding Operation
CBO	Congressional Budget Office
COG	Council of Governments
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
CWA	Clean Water Act
DEM	Digital Elevation Model
DU	Designated Uses
E. coli	*Escherichia coli*
EIA	Environmental Impact Assessments
EPA	Environmental Protection Agency
FA	Factor Analysis
FC	Fecal Coliform
FOIA	Freedom of Information Act
FIB	Fecal Indicator Bacteria
GI	Green Infrastructure
GSI	Green Stormwater Infrastructure
HUC	Hydrologic Unit Code
LID	Low Impact Development
MOU	Memorandum of Understanding
MPN	Most Probable Number
MS4	Municipal Separate Storm Sewer System
NEPA	National Environmental Policy Act
NGO	Non-Governmental Organization
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
pH	Hydrogen ion Concentration
POTW	Publically Owned Treatment Works
PRESS	Prediction Sum of Squares
R^2	Coefficient of Determination
ReWa	Renewable Water Resources
RRWQG	Reedy River Water Quality Group
SC	South Carolina

List of Acronyms (Continued)

SCAAS	South Carolina Adopt-A-Stream
SC DHEC	South Carolina Department of Health of Environmental Control
SSE	Sum of Squared Errors
SSO	Sanitary Sewer Overflow
SSS	Sanitary Sewer System
SWANCC	Solid Waste Agency of Northern Cook County
TMDL	Total Maximum Daily Loads
U.S.	United States
USGS	United States Geological Survey
VIF	Variation Inflation Factor
WHAT	Web-based Hydrograph Analysis Tool
WHO	World Health Organization
WQS	Water Quality Standards

CHAPTER ONE: INTRODUCTION & CASE STUDY OVERVIEW

Introduction

Since the adoption of the Clean Water Act (CWA) in 1972, surface water quality has seen significant improvements in point source pollution reduction; however, nonpoint sources (NPSs) continue to contribute high levels of pollutant loads into our local waters. The current method to address this concern is to analyze each pollutant separately and where there is noncompliance to the imposed standard, either Total Maximum Daily Loads (TMDLs) or alternative restoration efforts are implemented to address the pollutant(s) of concern. Once the TMDLs have been set, one strategy to achieve them is a Section 319 grant, which is available to various entities such as municipalities, counties, and water dedicated groups and companies in the form of state approved funding to execute a watershed based management approach that reaches diffuse sources. Although this approach can be localized to a specific problem, success is not guaranteed and these grants do not mandate that all stakeholders will be represented in the planning process (Dyckman, forthcoming). The impact of land use choices on urban stream systems and pollutant levels are not well understood. One pollutant category, bacteria, which is analyzed for the indication of fecal contamination in our local waters is a prime example of a diffuse and enigmatic pollutant. Recently in South Carolina (SC), the standard for measuring this pollutant shifted from fecal coliform (FC) to *Escherichia* coli (*E. coli*). It is difficult to pinpoint causal relationships to specific land uses, both natural and/or manmade, without expensive sampling and testing, and even then, results can be inconclusive (Rowny and Stewart, 2012; Crim, Schoonover, and Lockaby, 2012). Using

Greenville County, South Carolina waters as a case study, I compiled the historical and current sampling record for analysis to better understand the condition of *E. coli* levels within this study area. A comprehensive approach, including all of the key stakeholders' data for Greenville County has not been engaged at the local level. I sought to discover if a correlation could be made between urbanized land uses and *E. coli* impairments in Greenville County. And if so, how could land use planning policy address this relationship?

The results of this research are critical for both public and private entities, as planners, engineers, landscape architects, hydrologists, and developers engage land use planning and water quality. Urban streams are important from a planning standpoint, as they serve as a focal point for the communities that surround them. From larger rivers such as the 240 mile San Antonio River in Texas and the 340 mile James River in Virginia to smaller rivers such as the 80 mile Charles River in Massachusetts and the 65 mile Reedy River in South Carolina, these waterbodies are iconic features for the cities through which they flow. Urban rivers provide recreation, economic benefits, tourism, scenic beauty, and in some cases drinking water to those whom live around and visit their locations. It is imperative that all persons involved with planning surrounding land uses and stream health work together to maintain the environmental integrity of these waterways so that they can remain an asset that everyone can continue to utilize and enjoy.

Greenville County Waters: Case Study Overview

Greenville County was chosen for this case study for several reasons that are explained in greater detail in **Chapter 3**. The overarching reasons are due to data availability, the type of data available, and the unique land cover and land use characteristics within Greenville County. A third of the available *E. coli* data is along the main stem of the Reedy River, which is within the Saluda Watershed, hydrologic designation 03050109. The Reedy River is not only an iconic natural resource and amenity for locals and visitors alike, but it has a rich history as a home to many mills throughout the centuries. Beginning in 1776, Richard Paris established a corn mill and many additional mills would follow, bringing both economic growth and hydrologic and ecologic stress to the Reedy (McKoy, 1969). The Reedy has been both admired for its beauty and abused during the textile boom (from the late 19th century to the 1970s). Before the adoption of the CWA, the Reedy was referred to as the 'Rainbow Reedy', named for the various colors the River would flow depending on the discharge from the adjacent textile mills (Nolan, 2014). Today, this expression is often mentioned to remind residents how far water quality has come since the enactment of the CWA. Like others in the United States (U.S.) the Reedy River continues to experience excessive pollutant loads, even under the CWA pollution control requirements. With an increase in urbanization, rapid land use changes, and climate change, the Reedy is constantly being affected by the human influences around it. From complications with aging infrastructure to litter, the Reedy continues to feel the impact of anthropocentric influences, including bacterial pollution, which prevent the Reedy River from a fishable and swimmable status.

Another third of the data comes from a riparian and lake network along the main stem of the South Tyger River that contains both Lake Cunningham and Lake Robinson, which are within the Tyger River Watershed, hydrologic designation 03050107. Lake Robinson was created by a dam for the purpose of water storage within the area and was completed in November of 1984 (Friends of Lake Robinson, 2009). Lake Cunningham is a smaller impoundment located downstream of Lake Robinson and was also created for water storage purposes. Both of these lakes serve as fishing and recreational use areas as well as drinking water sources for the surrounding community. The last third of the data available is from a variety of locations within Greenville County that provide insight to areas with more rural character, with higher proportions of forested areas, as well as areas rich in agriculture.

The Saluda watershed, which begins with the top most portion of Greenville County, has many entities working towards its maintenance. However, data sharing is not common across entities. The City of Greenville and Greenville County are an exception since during the summer of 2017, they signed a Memorandum of Understanding (MOU) to share their data, which are 6 and 8 years in the making, respectively. The headwater of the Saluda is considered pristine because it is highly protected and undeveloped. Both the North Saluda and Table Rock manmade reservoirs, found at the headwater, are two of three drinking water sources for Greenville. They have been protected since they were brought into service and there are no activities that could cause contamination threats according to the Office of Water (EPA, 2010). These reservoirs are also located in a completely undeveloped area of the watershed that is owned and protected by Greenville

Water Supply, which prohibits recreation. There is even a full-time staff member at Greenville Water that patrols the watershed to safeguard these reservoirs (EPA, 2010). Historical sampling data from the 1930s (Table Rock was made in 1930) and 1960s (North Saluda was made in 1961) indicate that there has been virtually no change in the quality of water within these two reservoirs, up to the present.

Greenville County Waters: Case Study Intention

Land use changes affect water quality, which is clearly evident in the ample literature on this topic (Goto and Yan, 2011; Crim, Schoonover, and Lockaby, 2012; Udenika Wijesinghe et al. 2009; Schiff and Benoit, 2007; to name a few). What is not clear is how we can best mitigate these concerns. By engaging the literature and closely examining Greenville County waters, I pursued a better understanding of the relationship between land cover categories, impervious land uses, permitting related to bacteria pollution mitigation, and the effects of these on *E. coli* levels, particularly as they related to the reduction of bacteria. I analyzed the current strategy for regulating NPSs, specifically *E. coli*, and its effectiveness in informing land use planning. The past, present, and potential future outlook for this work was considered and recommendations for strategies going forward are provided in **Chapters 4** and **5**. The goal of this research was to correlate urbanized land cover, and attempt to differentiate land uses via impervious surface types with *E. coli* impairments in Greenville County and from those results, provide insight to land use planning policy. Based on the unique land cover transitions mentioned above within Greenville County, the impacts of growth and development on *E. coli* should have been able to be isolated within this study. I

hypothesized that there was a relationship between land cover typology and impervious land uses with *E. coli* and I predicted that this study could lead to more informative policy adjustments. The null hypothesis was that no correlation could be determined between land cover or land use and *E. coli* levels in Greenville County.

The following literature review provides a brief overview of the CWA and the mechanisms within this statute that address or at least attempt to address NPS pollution. These mechanisms are explained and then critiqued for successes and failures as they have been applied. I also discuss bacteria as a specific pollutant that is a result of both point and NPS pollution in our waterways. I provide an overview of the origin of bacteria, as well as the implications for both human and ecological health risks, and then focus on *E. coli* as an indicator of water quality. I give a brief summary of South Carolina bacterial impaired waterbodies to provide a baseline of understanding with respect to selecting the waters within Greenville County as a case study. I discuss the state of current knowledge on the relationship between *E. coli* and land uses and the recommended site design interventions to reduce bacterial loads in our waterways. I then present my case study, research design, analysis, findings, limitations, and conclusions. Finally, I discuss the implications of the research results for planners and the need for future research to further bridge the land use water quality gap.

CHAPTER TWO: LITERATURE REVIEW

The Clean Water Act: A Brief Overview

The foundational law governing surface water protection, enacted in 1948, was the Federal Water Pollution Control Act. Prior to this date, diminutive federal legislation for environmental pollution had been enacted and "environmental control was traditionally viewed as protecting the health, safety, and welfare of the people and therefore, was a function of the states under their police powers" (Guruswamy, 1989, pg. 465). This legislation received major revisions in 1972, shortly after the enactment of the National Environmental Policy Act (NEPA) and the founding of the Environmental Protection Agency (EPA), which were both in 1970. These revisions significantly expanded federal oversight of the United States' surface water resources and became known more commonly as the Clean Water Act (CWA). There were six original legislative goals that were established by these 1972 amendments, and they read as follows:

> 1. *"It is the national goal that the discharge of pollutants into the navigable waters be eliminated by 1985;*
> 2. *It is the national goal that wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983;*
> 3. *It is the national policy that the discharge of toxic pollutants in toxic amounts be prohibited;*
> 4. *It is the national policy that Federal financial assistance be provided to construct publicly owned waste treatment works;*
> 5. *It is the national policy that areawide waste treatment management planning processes be developed and implemented to assure adequate control of sources of pollutants in each State;*
> 6. *It is the national policy that a major research and demonstration effort be made to develop technology necessary to eliminate the discharge of pollutants into the navigable waters, waters of the contiguous zone, and the oceans; and*

> *7. It is the national policy that programs for the control of nonpoint sources of pollution be developed and implemented in an expeditious manner so as to enable the goals of this Act to be met through the control of both point and nonpoint sources of pollution."*
> *[Note: Number 7 was added on February 4, 1987]*
> (CWA, 1972, para. 1)

The goal dates for items one and two have long since passed and the U.S. is still working towards completing these, 45 years later. The state and federal governments have had inadequate approaches to attain these goals and a lack of implementation, leaving our rivers incapable of reaching fishable and swimmable standards (Cosens and Stowe, 2014). At the onset of the environmental policy legislation, a fragmented approach began to take shape in regards to both media (air vs. water) and assessment. The Clean Air Act (CAA) and CWA were initiated separately, with their own legislative actions and goals, disregarding their interactions in nature. Also, actions performed by the EPA are essentially exempt from NEPA requirements, which means the EPA is not obligated to complete Environmental Impact Assessments (EIAs). EIAs examine the potential environmental effects that would result from a project. Guruswamy (1989) remarks that the rigorous legislative goals set forth by the CAA, and similarly the CWA, precluded the EPA from the formal assessments due to the time constraints, an obstacle that was corroborated by the court in *Portland Cement Ass'n v. Ruckelshaus* (1973). Yet, even without the requirement of EIAs, the aforementioned water quality goals were too ambitious, a failure that will be discussed further below.

Many mechanisms exist within the CWA to better regulate water pollution issues. A brief overview of these concepts and definitions are as follows. First and foremost, the EPA has segregated pollution by point source and NPS. As defined by the CWA "point

source means any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged" (CWA, 1972, § 502). The CWA makes an exception for "agricultural stormwater discharges and return flows from irrigated agriculture", placing this in the NPS category (CWA, 1972, § 502). The CWA does not formally define NPSs within the Act; however, the EPA cites many forms of the definition within their own publications and on their website. In summary, NPS pollution is everything that point source is not. It typically results from land runoff, precipitation (rain, snow, or fog), drainage across an area of land, seepage through the ground, atmospheric deposition (from human induced pollution), or hydrologic modification, i.e., human alteration of a waterbody. As the runoff makes its way to a local waterway, it carries along both natural and human-made pollutants. The cumulative nature of NPS pollutants creates a challenge in both identifying the cause of the pollutant on a body of water and the mechanism(s) to mitigate the problem.

The CWA requires that water quality standards (WQS) are set and followed to control water quality pollution concerns as part of Section 303. The WQS serve two key purposes; first, to define goals for a waterbody by "designating its uses, setting criteria to protect those uses, and establishing antidegradation policies to protect waterbodies from pollutants"; and second, to serve as the foundation for "water quality-based limits in NPDES [National Pollutant Discharge Elimination System] permits" (EPA, July 2015, para. 2). Together these standards determine if a waterbody is impaired and if a target

TMDL is needed to begin restoration of that waterbody. Section 303(d) specifies the need for states to identify those waterbodies which do not meet the standards set forth by the WQSs and to prioritize them based on the severity of the pollutant loading to control these concerns. States are permitted to devise alternatives to TMDLs, which have become known as category 4b waters. To be considered for this list, "technology-based effluent limitations" or "more stringent effluent limitations" must be implemented by the State, local, or federal authority, or "other pollution control requirements" such as Best Management Practices (BMPs) must be put into place and be stringent enough to be water quality standards (Monschein and Reems, 2009, pg. 778).

Section 402 establishes the right of an eligible state entity to issue permits for point source discharges called NPDES permits. Today there are over 215,000 permits for traditional industry and municipal releases as well as stormwater discharges (Copeland, 2016). Since 1977 these permits have required the holder to apply best practicable control technology (BPT) or best available technology (BAT) depending on the source. NPDES permits limit the pollutant load, dictate a deadline for compliance, and mandate effluent monitoring and record keeping for up to five years before renewal is required (Copeland, 2016).

Finally, it is worth noting two additional sections of the CWA that speak directly to NPSs and have made an impact on the way in which states have begun to address the negative externalities of these pollutant sources. Section 208 specifically directs states and areawide agencies to create management plans for water quality, identifying and addressing both point and NPS pollution, including agriculture. The management of these

plans at the state level varies. In South Carolina, for example, there are six Councils of Governments (COGs) that serve as planning agencies for 24 of the counties within the state, while the remaining 22 counties are under the jurisdiction of the South Carolina Department of Health and Environmental Control (SC DHEC). At the onset of the CWA, between the years of 1974 and 1981, the Federal government provided grants to states for over 200 water quality management programs (EPA, 1984). After the 1987 amendment to the CWA, Section 319 included a more formal acknowledgement of NPSs, though the revision still left the management control at the state level. Section 319 initiatives could be used to identify unsuccessful plans from Section 208 programs, but again these were not federally mandated. Section 319 also included the recommendation to incorporate groundwater protection within state plans, and this section incentivized plans by providing federal financial assistance to support "demonstration projects and actual control activities" which could cover up to "60% of program implementation costs" (Copeland, 2016, pg. 4).

In summary, the CWA filled a major void in federal regulation around water quality concerns in the U.S. Surface water quality has seen significant improvements by the reduction of point source pollution, however, NPSs continue to contribute high levels of pollutant loads into our local waters. The CWA focused on two major components, first the authorization of "federal financial assistance for municipal sewage treatment plant construction" and second the "regulatory requirements that apply to industrial and municipal dischargers" (Copeland, 2016, para. 3). Depending on the aspect of water quality concerns, the Act provided both comprehensive (point source) and loose (NPS)

mandates for improving water quality. The enactment of this legislation has allowed for many successes but has left significant gaps that perpetuate the water quality concerns within the U.S. Even with more overt inclusion of NPSs due to the 1987 amendments to the Act, U.S. waters are still plagued with diffuse pollutant sources.

The Clean Water Act: Successes and Failures

Scholarly debate on the disjointed approach to environmental protection ensued shortly after 1972 and has continued as the EPA mandates remain vague and individual states seek to mitigate pollution concerns without concrete requirements. Environmental regulation at the state level has been inconsistent in motivating desirable outcomes, with scholars noting the potential for a “race to the bottom” between states as competition to keep industry has allowed for more lax regulation and in some cases suboptimal results (Swire, 1996, pg. 68). The incremental tactics the federal government has continued to take when addressing pollution from air to water has also carried over onto pollutant interaction regulation. For example, the CWA does not take into consideration the reality of multi-pollutant reactions (Klein, 2013). The EPA even published an article in 1999 that acknowledges the threat of cumulative effects of the environment. The scope of regulating cumulative effects lies only with federal projects under NEPA (EPA, 1999). These are complicated to predict since there is no “cookbook” method that has been devised to determine these effects (EPA, 1999, para. 1). This piece meal approach to pollution reduction has been regarded as one of many downfalls to the CWA. It is readily acknowledged that the way in which we address pollutants in our waterways is inconsistent (point source vs. NPS), but it may also be illogical, since the current strategy

ignores multi pollutant interactions, which can exacerbate human and ecological risk. For example, nitrogen and phosphorus together can lead to algae blooms, but the individual elements are treated separately by their own WQS and TMDL. Air pollution regulation is actively engaging a “one atmosphere” approach, but a similar conversation regarding water has failed to garner attention (Dominici et al., 2010, pg. 187).

Finally, with respect to strategy, only certain pollutants are regulated by the EPA. Due to recent advances, our knowledge of chemical contaminants in water has vastly increased and the source is mainly anthropogenic (Templeton, Graham, and Voulvoulis, 2009). Although the levels of these containments in our waters is low, the “environmental and human health consequences (e.g., cancer risk and adverse reproductive development)” may be both “significant and widespread” (Templeton, Graham, and Voulvoulis, 2009, pg. 3873). Wastewater water effluent, or the treated discharge from a wastewater treatment plant, contains many of these chemicals even post treatment. One negative externality that has been identified is fish sensitivity to steroid [o]estrogens (Martin and Voulvoulis; Lopez, 2010). There are less definitive statements being made about the effect of these endocrine disrupting drugs on humans, due to the lag time of exposure before the “manifestation of a clinical disorder”, as well as the timing of exposure (Safe, 2004; Lopez, 2010, pg. 21). Even so, it is important to note that our understanding, and how to even begin to test for these concerns, is still in the early stages. In 2010, Jacki Lopez, a staff attorney for the Center for Biological Diversity, petitioned the EPA requesting that criteria for endocrine disrupting chemicals get added to the federal water quality standards. These chemicals along with many other

pharmaceuticals and personal care products, which are increasing in number, are constantly entering our waters through raw or treated sewage. The EPA has not taken a stance on these as of yet.

By labeling water pollution as NPS and point source and regulating them separately, the EPA within the CWA has narrowed their ability to completely address these concerns, preventing the first two goals of the CWA from being fulfilled. These human created distinctions of point and NPS are a concept that nature does not recognize. Pollution, regardless of the source, in our local waterways can have detrimental effects. To muddy the waters further, the statute creates linguistic confusion, which is a common concern with legislation in general, but continues to cause consternation as federal, state, and local entities work towards clarity for environmental protection. The CWA begins with the phrase "The object of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (CWA, 1972, para 1). Klein (2013), points out that the word "integrity" along with others embedded in the act such as "navigable," "point source," and "pollution" have caused confusion and have left the understanding of this Act to be broad and open for interpretation (pg. 40). The phrase 'discharge of any pollutant' which dictates the need for a NPDES permit is one example of this interpretation challenge. Dornsife (2005) observes that not only does the EPA disregard dam releases as a downstream pollutant source, but the definition that determines the implementation of an NPDES contains the ever-debatable phrase, "navigable waters" (pg. 178). 'Navigable waters' is a complex phrase that, to this day, is misleading because of Congressional failure to generate a viable definition. Hence,

judicial interpretation and lack of a concrete distinction of these waters can exacerbate the confusion rather than invoke clarity, which was observed in both *Rapanos* and *Solid Waste Agency of Northern Cook County (SWANCC)* with navigable waters and the significant nexus test (Glicksman, 2010; Klein, 2013). When there is an absence of judicial input, the CWA has enabled personal interpretation, segregating the implementation strategies amongst the different states; for example, interpreting the meaning of "direct implementation of restoration projects" for section 319 grants (Hardy & Koontz, 2007, pg. 303).

The initial and explicit intention of the CWA, was to address the obvious forms of pollution, or the low hanging fruit: industrial and municipal point sources. These pollutant sources were the easiest to control as they have a discrete conveyance into a waterbody. They are also often publicly noticed. Similar to the Reedy River being referred to as the "Rainbow Reedy", other waterbodies experienced blatant point source pollution, including the Cuyahoga River in Ohio that became known as the River on Fire from industrial waste. It should be acknowledged that the CWA took a significant bite out of the overwhelming pollution problem, clearly recognized in the 1960s and early 70s, by addressing these point sources. The unfortunate draw back, about which the EPA has made multiple forthright statements, is the lack of control with NPS pollution that continues to affect water quality. Today it is estimated that NPS pollution contributes to greater than 50% of all surface water pollution in the United States (Copeland, 2016). This is a distressing statistic for a precedent that was set 30 years ago with the 1987 amendments to the CWA, encouraging states under Section 319 to "develop and

implement [NPS] pollution management programs" (Copeland, 2016, pg. 4). Clearly the lack of mandatory implementation for addressing NPS pollutants has prevented a similar success story for NPS pollutant loads. These recommendations also enable states to allow "political salience" and "significant interest" to influence their decision to take on NPS pollution enforcement, rather than solely considering human and ecological risk on its face (Craig and Roberts, 2015, pg. 2). Glicksman (2010) states that "Congress's unwillingness to adopt, or force states to adopt measures to control NPS pollution" is a reason the CWA has not performed more commendably (pg. 101).

WQS are another example of water policy that lacks uniform treatment. All states have the power to create more strict versions of the WQS, and although this may be perceived as a benefit, once again the notion of state specific guidelines to water quality concerns does not always make hydrological sense, simply because waterbodies cross state boarders. If there are two different standards for hydrologically connected waters, the stricter standard is set in vain, unless the EPA demands that they are consistent, which they do not always mandate. Also, if a state refuses to set standards the EPA will do so for them, which again can cause discrepancy across a watershed that crosses state boundaries. As previously stated, nature does not follow political boundaries.

On that note, there have been some examples of positive outcomes from the EPA stepping in to implement a standard. For example, in California, the state failed to set a TMDL for the Garcia River from the WQS, which enabled the EPA to set strict standards for sediment loading on the River (Christopher, 2001). This led to a suit, *Pronsolino v. Marcus/Pronsolino v. Nastri,* which ruled in favor of the EPA, enabling the organization

to set TMDLs on waters solely affected by NPS pollution (Hale, 2001). This environmental gain came about largely due to dissatisfied environmental groups, whom were frustrated by the lack of TMDL implementation. Section 319 and TMDLs were mostly ignored until the 1990s, when dissatisfied environmental groups began to bring lawsuits against the EPA to hold them accountable to the statute (Hale, 2001). Some of these cases held in favor of environmentalists and empowered the statute, such as *Scott v. City of Hammond*, which established the “constructive submission” concept, mandating that the EPA issue TMDLs when a state had failed to do so (Hale, 2001). However, some litigation held in favor of the EPA taking a backseat and allowing lackluster mitigation efforts to remain in place, such as *Sierra Club v. Brown*, which defined “state action” and held that Minnesota’s “submission of an alleged ‘handful’ of TMDLs sufficed to allow the EPA to abstain from action” (Hale, 2001, pg. 989).

Funding opportunities are another topic that garners critique within the CWA. Section 208 and 319 funding opportunities were and have continued to be voluntary in regards to NPSs, which leads to inconsistent participation across the states and allows political boundaries to determine participation and progress rather than watershed boundaries. Again, natural boundaries and human determined land divisions are not aligned. Section 208 ultimately failed to control NPSs because of the malleability of the legislation, the controversial and politically sensitive characteristic of the Section as it related to agricultural interests, and the fact that funding and the state programs ceased to exist beyond 1980 (Zaring, 1996; Szalay, 2010). The EPA decided in 1980 that it would “not attempt to aggressively control NPS activities” and Congress blamed them for the

lack of supervision in regards to the state programs, which ultimately lead to the diminished enthusiasm to address NPSs (Zaring, 1996, pg. 524). Sirianni (2006) corroborates this sentiment of failure, noting the combination of the following reasons that Section 208 implementation was both “messy” and “disappointing”: “limited statutory authority and local political clout, especially over land use; delayed administrative guidance and stop-and-go funding that disrupted civic and institutional capacity building; [and] relatively low status of the ‘soft’ watershed staff in the agency relative to those from the ‘hard’ disciplines of law and engineering” (pg. 19). Even with this laundry list of problems, Sirianni (2006) does note a few silver lining aspects of this Section that should not be ignored. Section 208 did create a framework for regional water-quality management planning, motivating hundreds of local associations to focus on water planning and to build collaborative relationships across entities around water concerns (Sirianni, 2006). This point raises another critical facet to the water planning dilemma: planner involvement.

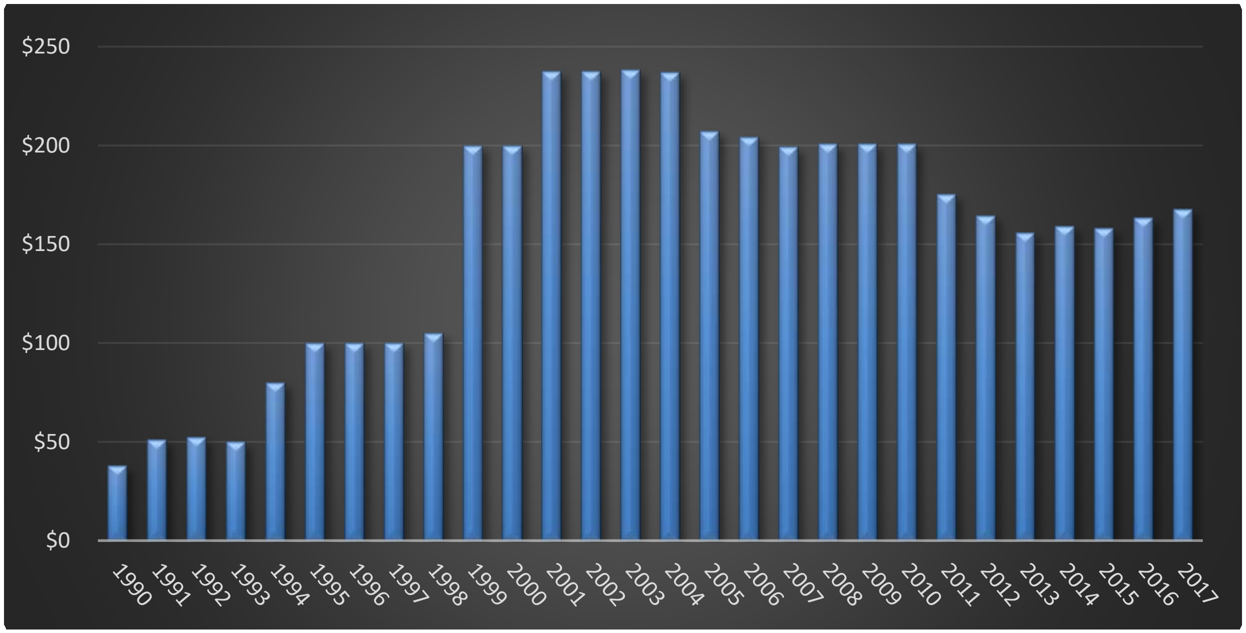
There is inconsistent participation by planners in regards to strategic planning for improvements to our local waterways. The 2016 Water Working Group Survey of planners revealed that three quarters of those surveyed “were not involved enough in water planning and decisions” and that essentially their interactions with other water management professionals is inadequate (APA Water Working Group, 2016, pg. 4). At a local scale, Dyckman (forthcoming) completed a comprehensive study on this topic within South Carolina, and she discovered that an alarming 82.5% of planners who responded to a state administered survey by the SC chapter of the American Planning

Association (APA) were not involved in Section 319 processes at all within their watershed. As growth continues to expand within U.S. cities and more natural land cover areas become developed, it is critical that we begin to take a more collaborative approach to water planning. Currently, there is no consistent, cooperative approach when making both land use and water planning decisions. This is not surprising, since thorough and meaningful stakeholder involvement in a watershed planning process relies on time, money, and lots of patience. Margerum (2002) expresses the importance of "effective communication, collaboration, and interaction" which are foundational to effective planning practice (pg. 251). If planners are not brought to the table at the onset of water policy conversations, consensus will not be met, because a key stakeholder will be missing. Planners work to control land uses by creating comprehensive plans and implementing zoning for the purpose of curbing some of the negative externalities of unrestricted land use, yet they are not always tied to water quality polices. Thus far, these tools have proven to be inconsistent and potentially unsuccessful; in some cases, they create conflict between environmental concerns and development desires (Christopher, 2001; Swire, 1996). To mitigate diffuse pollutant concerns from NPSs, a call for updated land use regulation has been noted in the literature, especially since these planning tools often "mandate increased amounts of impervious cover" (Hale, 2001; Schiff and Benoit 2007, pg.. 727).

There are other aspects of Section 319 grants that hinder their successful implementation. These grants consist of both base and incremental funds. The base funds are more flexible and can be utilized towards any aspect of the NPS management

program that has been approved by the EPA, while the incremental funds must be used towards the restoration of waters found on the states' 303(d) list (this list will be explained in more detail below). Hardy and Koontz (2007) performed a coded study of state NPS coordinators and determined that the top three areas states would like to see change with respect to the Section 319 program were as follows: the inconsistent and fluctuating budget, the desire for more funds allowed for stormwater concerns, and the lack of structure for program implementation. The most recent fund allocations for Section 319 grants are shown below (see **Figure 1**). In the year 2003 there was the highest allocation of funding and as of 2017, the funding had dropped by over $70 million dollars. Hardy and Koontz's (2007) interviews were conducted when the budget was nearly $40 million dollars higher than it is today. Arguably, the outcry from NPS coordinators for funding concerns would be amplified should states be surveyed again. Also, at present, only incremental funds are capable of being used for stormwater. This was noted to be challenging especially for Phase II communities, which are municipalities that were required to have stormwater management programs beginning in 1999 (Hardy and Koontz, 2007).

Figure 1: Section 319 Funding by Year



Values are in millions and rounded to the nearest $100,000

Note: Data for grant funding from EPA (2017), retrieved from https://www.epa.gov/nps/319-grant-program-states-and-territories.

Even before the 1987 amendments of the CWA, which overtly included NPSs, the EPA was upfront and explicit about their concern for NPS pollutants in reports to Congress and the public. In the 1984 EPA Report to Congress on NPS pollution, NPSs were noted as a pervasive problem that plays a major role in contributing to many of the water quality problems that remained in U.S. waters. This report noted that the National Stream Quality Accounting Network analysis at the time indicated that most pollutants were worsening. The EPA also admitted in this report that "gaps in problem assessment, control technology, and program approaches remain" and the only glimmer of hope is that "many NPS control efforts have been initiated at the State and local levels and provide a sound basis for intensified NPS activities" (1984, pg. xi). The follow-up action steps reflect this sentiment with vague language and a delegation of ownership to solve NPS pollution concerns into the hands of the states. This added to the inconsistencies across state borders and NPS BMPs that remain today in the U.S.

When the amendments to address NPS pollution control were implemented in 1987, they lacked both structure and strength. Section 319, as it is written, only recommends that states take action to control NPSs; hence, it is completely voluntary. By 2006, all states had adopted some watershed based collaborative planning approaches, but the strategies lack a coherent approach (Hardy & Koontz, 2007). Without structure and specific measures to address NPS pollution, which Congress refuses to adopt, the CWA will continue to fail as far as surface water quality is concerned (Glicksman, 2010). There are many federal failures that have been cited as explanations for the lack of NPS mitigation success efforts, including lack of regulation, especially with respect to the

agricultural industry, inadequate incentives and funding, lack of administration, and "congressional reluctance to encroach upon the right of states to control land use" (Hale, 2001, pg. 983). That being said, there is also a lack of state ownership to this concern, including a general lack of initiative (Hale, 2001). Despite these viable critiques of the Act, it is important to remember that NPS pollution has diffuse origins, and hence remedies lean heavily on regulation of land use and zoning, which are more typically under state control (Hale, 2001). Hence there is a delicate balance of police power to maintain, which is an additional reason for the lack of immediate solutions for NPS pollution.

Given these aforementioned concerns, complaints, and observations, academics and journalists have voiced a need to revise and update the CWA. Klein (2013) focuses on the need to have a "more progressive and holistic approach to environmental regulation" (pg. 50). Prud'homme (2011) goes a step further stating that the "agencies in charge of enforcing these laws must be reinvigorated and given the backing to do their job" (pg. 350). What remains shocking are the horrifying facts regarding water quality in this country that alone do not seem to stimulate better policy and increased funding (see the following bacteria focused sections, *Bacteria as a Pollutant* and *Fecal Bacteria: Ecological and Human Health Concerns* in **Chapter 2** for specific facts). Water is a resource that humans rely on for basic survival. The current incremental approach to addressing water quality in the U.S. has dangerous implications, especially as we plan for the future. Adaptive management (AM), which is an iterative learning process, is arguably preferable to the status quo, especially since the water issues' magnitude is

increasingly compelling, causing states to compact across boundaries to control water quantity and quality. Gerlak (2006) states that AM is an “interdisciplinary approach,” which “seeks action in the face of limitations of scientific knowledge and the complexities of large ecosystems” and “it does not postpone decisions until enough is learned about the ecosystem” (pg. 244). This tool or approach to addressing large scale environmental concerns was endorsed by the National Research Council in 1992 (Gerlak, 2006). The above discussion should provide motivation to update the current CWA, but the following complications with bacterial monitoring further reinforce that need.

Bacteria as a Pollutant

Stormwater carries NPS pollutants across all surfaces, towards local waterways or in the case of an urbanized area, towards stormdrains, which lead directly to local waters. The permeability of a surface dictates the volume and velocity of the runoff. As little as 10% land use change in the adjacent watershed can lead to deteriorated habitat quality in a stream (Sedlak, 2014). More specifically, increases as little as 5% total impervious area within a watershed can cause an impairment (Schiff and Benoit, 2007). Bacteria, one of many pollutants that gets carried along by stormwater, has an array of sources, both point and NPS, making it even more difficult to pinpoint a cause. Both sanitary sewer and combined sewer overflows as well aging infrastructure can lead to both point source and NPS pollution depending on if the sewage backs up on land adjacent to a waterbody (discussed in more detail in the following section). Waste water treatment plant effluent is point source. Household pet waste is often NPS, while livestock fecal matter and wildlife fecal matter is traditionally thought of as NPS though if these animals defecate

directly within a waterbody they are essentially creating point source pollution. All of these sources, both point and NPS, increase the potential for pathogenic pollution in our nation’s waters.

Since the onset of sanitary waste infrastructure in this country, there have been two primary strategies for dealing with human sanitary waste. Combined sewer systems (CSSs), introduced to the U.S. in 1855, convey both stormwater runoff and sanitary wastewaters to a publically owned treatment works (POTW) center. The treatment component was not added until the early twentieth century, and initially the waste was directly dumped into local waterways (Tibbetts, 2005). The major downfall for this design is that during a heavy rainfall, these combined sources overflow the system and discharge untreated effluent directly to surface waterbodies. This is called a Combined Sewer Overflow (CSO). The segregated system called Sanitation Sewer Systems (SSS) were introduced to the U.S. in 1875 and eventually became more prevalent than CSSs (Burian, et al., 2000). SSSs can also overflow during heavy rain events and are called Sanitary Sewer Overflows (SSOs).

NPDES permits are required for all CSO and SSO locations that directly convey to a water of the U.S. per the EPA (2004). Although this regulation exists, these only help to mitigate the negative effects CSOs and SSOs have on human health and the environment, which are still a pervasive problem. These permits do not address the many bacterial NPSs, including when CSOs and SSOs overflow and precipitation washes the waste into a stormdrain. In 2004, the EPA published a report to Congress, reiterating that these systems are a current threat to both human health and the environment. This

document remains the most current and complete publication produced by the EPA on CSOs and SSOs to date (EPA, 2004). CSSs are found in 32 states, including the District of Columbia, but are predominantly in the Northeast and Great Lakes regions. As of 2004, there were 746 communities with CSSs, 9,348 CSO outfalls that were identified and regulated by 838 NPDES permits, and from these, approximately 850 billion gallons of untreated wastewater and stormwater have been annually released in the U. S. (EPA, 2004). All 50 states, including the District of Columbia, collectively operate 15,582 SSSs, with 4,846 additional satellite SSSs that do not provide treatment, and between 23,000 and 75,000 SSOs releasing an estimated 3-10 billion gallons of untreated wastewater, annually in the U.S. (EPA, 2004).

Overflows are not the only method by which bacteria reach U.S. waterways. As infrastructure ages, a litany of complications can arise. Tree roots can work their way into joints and cracks, creating leaks and reducing pipe capacity (Sedlak 2014). According to the Sustainable Solutions Corporation (2017), pipe material can also result in leaks due to corrosion (leading cause), degradation, joint failure, and oxidation. Soil conditions, depth of installation, internal and external loads, temperature changes and bedding conditions are additional variables affecting pipe failure (Sustainable Solutions Corporation 2017). Leaks not only allow internal pipe material to seep into the surrounding ground water, potentially contaminating it with pathogens, but they also make the pipe susceptible to soil and groundwater intrusion, which can cause capacity issues, and total pipe failure due to collapse (Sedlak, 2014; Sustainable Solutions Corporation, 2017). The capacity concern leads to increases in CSOs and SSOs, which can result in sewage backup onto

streets that makes its way into the stormdrains and then the local surface water. Leaking pipes have also been shown to contribute point source bacterial contamination to ground water during dry conditions, as the lowered water table pulls sewage into the ground (Davis et al. 1995; Whitlock et al. 2002). These mechanisms provide a broad overview of ways in which bacteria can enter the water from human fecal matter.

Pathogens from fecal matter also enter surface water from household pets, livestock, and wild animals when runoff occurs. Manure from livestock is permitted to be spread across agricultural land, and although setbacks from waters of the U.S. exist, in South Carolina there is record of people misbehaving and violating these rules when they land apply (SCDHEC, personal communication, February 12, 2012). The negative human health effects from these various sources of fecal bacteria differs based on the designated use of the waterbody affected (e.g. recreational, protected etc.), as well as the concentration of the contaminant. Some research suggests that human fecal matter is a greater public health risk than non-human fecal matter (Moe, 2002; Scott et al., 2002; Carson et al., 2005; and Cao et al., 2017). That being noted, one of the most harmful strains of *E. coli*, O157:H7, is found in both human and animal feces (Moe, 2002). Understanding the source of the fecal matter within a waterbody may better provide recreational activity recommendations as well as policy recommendations to reduce bacterial loads in our waters. This body of research also offers abundant alternative solutions to the current methodology for bacterial analysis, which will be presented below.

Fecal Bacteria: Ecological and Human Health Concerns

Feces carry millions of microorganisms, some of which are pathogenic. These pathogens include bacteria, viruses, and parasites; fungi are not prevalent in wastewater, though it can be a detrimental result from moisture caused by sewage backups in homes (Dorfman, Stoner, and Merkel, 2004; EPA, 2004). These pathogens cause a litany of symptoms and illnesses when they reach the infective dose (i.e., the right number of pathogens required to cause a subclinical infection) and often include gastrointestinal issues, vomiting, diarrhea, and even death (EPA, 2004). Exposure to these pathogens can occur from contact or ingestion of contaminated water, or consumption of affected shellfish (EPA, 2004). It is estimated that as many as 9 million cases of waterborne diseases are expected to occur each year in the U.S. though it is difficult to quantify as many cases go unreported (Rose et al. 2001). Not all of these are a result of drinking water. Recreational activities including swimming, fishing, and boating can also lead to disease and even death and the extent to which these affect human health will vary with climatic changes including temperature fluctuation and extreme weather events (Rose et al., 2001; Patz et al. 2000)

The health of aquatic life is also affected by fecal contamination. Oxygen loss, which can result from too much sewage being conveyed into an ecosystem, can lead to fish kills and habitat loss (Dorfman, Stoner and Merkel, 2004). Also, once the amount of discharged sewage has surpassed a critical level, the dissolved oxygen will be “depleted faster than it can be replenished” and according to the EPA this alone causes “37 percent of the reported water quality problems in impaired estuaries” (Dorfman, Stoner and

Merkel, 2004, pg. 15). Cumulative toxins within aquatic species can destabilize interactions within a food web and include human consumption within the food chain (Rose et al., 2001). Human waste also contains nutrients, similar to other mammalian manure, which we frequently use as a fertilizer and due to this characteristic, human waste can have the same effect on aquatic plants as fertilizers do on agricultural crop yields. Too much of these nutrients, including phosphorus and nitrogen, can lead to eutrophication (Dorfman, Stoner and Merkel, 2004; Mallin et al., 2007). Mallin et al. (2007) studied a sewage spill in North Carolina (NC) in 2005 that led to hypoxia (void of adequate oxygen for life), killing fish and leading to algae blooms. In 2016, Florida experienced a massive algal bloom credited to water releases from Lake Okeechobee, which received runoff from specific agricultural land uses as well as human waste (Spencer, 2016). This was noted to have an economic effect on the area as well, and this is not the first instance of fecal contamination having a deleterious effect on the economy. Elkhorn coral in the Florida Keys has seen a devastating decline in population due to human digestive tract bacteria, which has also created significant economic concerns for this area since it is one of the more sought-after diving destinations in the world (Dorfman, Stoner and Merkel, 2004).

Finally, pathogens can also live for extended periods of time in the bottom sediments of waterbodies, remaining a threat to human health, especially if disturbed and suspended in the water (Dorfman, Stoner and Merkel, 2004). It has been known for nearly half a century that FC and *E. coli* remain viable within freshwater bottom sediment and as early as 1905, it was proposed sediments could be tested to evaluate bacterial

pollution (Geldreich, 1970; Savage, 1905). Pachepsky and Shelton (2011) discovered that until recently (the last two decades), this concept has been relatively ignored and the complexities behind it, suggest a much more complicated situation for water quality and bacteria than was originally assumed. Growth rates, die-off, predation, and high genetic diversity of *E. coli* in sediments make it incredibly challenging to pinpoint a source or cause for the bacteria (Pachepsky and Shelton, 2011). As planners and water quality focused entities continue to plan for solutions to bacterial pollution, the implications of Pachepsky and Shelton's (2011) study are critical to consider, as there is still "substantial uncertainty in detection, monitoring, and control of microbiological water quality and stream impairments" (pg. 1097). Some studies have even indicated that elevated stormflow events could be a result of "remobilized sessile bacteria stored within fluvial sediments" rather than solely from runoff itself (Pachepsky and Shelton pg. 1097). This research does not negate the body of literature that reveals the direct effects of land use on water quality, but it does add another layer of complication.

It is also important to note the survival of *E. coli* within surface water more generally. Wang and Doyle (1997) performed a detailed analysis focusing on five O157:H7 *E. coli* strains. O157:H7 causes foodborne and waterborne illness and exposure has been tied to both drinking water and recreational water activity (Wang and Doyle, 1997). At the time of this article the survival of this sometimes deadly strain of *E. coli* was poorly understood. Their research covered municipal water, reservoir water, and two recreational lakes and they discovered that at various holding temperatures, these strains survived anywhere between three and 13 weeks. Guber et al. (2015) found measurable *E.*

coli results at the end of their 32-day study that was focused on white-tailed deer fecal matter. The survival rate varied by temperature, as well as other environmental stressors such as protozoan predation, and until recently, very little research has been completed to understand the "transition from the gastrointestinal tract to aquatic habitats" (Wanjugi, P, Fox, G.A., and Harwood, V.J., 2016; Guber, 2015). For this reason, it is critical to understand compounding fecal sources on a waterbody from both point source and NPS; this is a characteristic that I considered in determining my research design discussed in **Chapter 3**. It appears that the multiple groups of scientists who are working to better understand this relationship conclude that more research should be done. However, the cost to gain this knowledge is prohibitive. This brings up another facet of this research that I did not consider for this study; namely, the potential for a comprehensive state or regional approach to water sampling. It is possible that there could be a sampling methodology that would better inform land use decisions and recreational water quality recommendations.

Current Testing: E. coli as an Indicator

The most commonly utilized bacterial indicators for the presence of pathogens within water were originally coliforms and fecal streptococci. In 2012, the EPA published an update to the 1986 Recreational Water Quality Criteria, once again recommending that fecal indicator bacteria (FIB), including *E. coli*, be utilized for analyzing fecal contamination in freshwater. In the 1986 publication, the EPA recommended that states "begin the transition process to the new [*E. coli* and enterococci] indicators" for freshwater and just enterococci for marine waters (EPA, 1986). However, there was no

impetus for states to make this transition as this report lacked a robust correlation between total coliform and FC and swimming related illnesses, and so many states retained the original indicator tests (O'Shea and Field, 1993). In the 2012 publication, the EPA cites the same studies from 1983 and 1984 as motivation for states to transition indicators as was previously stated in the 1986 report, again providing lack luster stimulus to switch (EPA, 2012). The 2012 publication also contradicts the fact that by the 1990s and continuing even now, research was and still is being performed to analyze the suitability of alternatives to *E. coli* and enterococci to better indicate pathogen risk (Ashbolt, Grabow, and Snozzi, 2001). This even affected my analysis, as some older NPDES permits within Greenville County are still utilizing FC rather than *E. coli* for water quality sampling purposes; I could not use the samples associated with these permits.

E. coli is a gram-negative rod that is found in both human and animal intestinal tracts and although most strains are nonpathogenic, their existence within a water sample indicates fecal pollution and the potential for disease exposure (Harmon, West, and Yates, 2014). *E. coli* is easy to culture and widely found in warm blooded vertebrates (e.g. dogs, cows, humans, geese). States have changed their standards to reflect the EPA's 2012 republished recommendation. South Carolina, for example, changed from FC bacteria to *E. coli* as the state WQS on February 28, 2013 (SC DHEC, 2017). Currently, the WQS for primary contact in recreational freshwater in SC is to not exceed "a geometric mean of 126 [most probable number (MPN)]/100 ml based on at least four

samples collected from a given sampling site over a 30 day period, nor shall a single sample maximum exceed 349 [MPN]/100ml" (SC DHEC, 2017).

E. coli as an Indicator: Efficacy and Complications

To further complicate matters, *E. coli* diversity within water varies by season, flow rate, and sample location (Udenika Wijesinghe et al. 2009). Rainfall and land use variation (e.g., seasonal agricultural use) could affect *E. coli* loads; however, proving that flow rate is positively correlated to *E. coli* levels is critical to the land use connection. Land use choices vary within a watershed and the timing of a sample (i.e., wet versus dry conditions) can influence the perception of water quality based on bacterial pollution. The grab sampling technique, which is a snapshot in time, is necessary for bacteria samples because of the short hold time and requisite incubation period to determine results. Because of the sensitivity of the bacterial capture process, creating a "representative hydrograph using automated samplers" is incredibly difficult (Clary et al., 2008). However, one study used an auto sampler for wet weather sampling and found no statistical difference with a non-refrigerated 24-hour hold time (McCarthy, 2009). Other parameters, such as turbidity, can be determined instantly in the field and can even be analyzed by an unmanned monitoring station. Correlations of turbidity to fecal bacteria have been analyzed on a large scale. Two example case studies where this strategy has been utilized to predict bacteria levels are in Kansas, which sought out to create a statewide model by sampling within selected basins (Rasmussen and Ziegler, 2003), and just outside of Atlanta, Georgia, in the Chattahoochee River (Lawrence, 2012). Both studies took significant time (three and eight years respectively), had key stakeholder

involvement, and were focused on better informing safe recreation within waterbodies that were frequently exceeding bacteria standards. In Kansas, the Department of Health and Environment as well as the EPA were involved in this study and the use of turbidity as a predictor for *E. coli* proved successful in most of the basins analyzed, but lacked significant correlation at all locations (Rasmussen and Ziegler, 2003). Fecal coliform showed a stronger correlation in their study than *E. coli*, which is interesting, since FC has been shown to be less suitable as a fecal indictor (Rasmussen and Ziegler, 2003). In the Chattahoochee River, both the National Park Service and the U.S. Geological Survey partnered for this project and they revealed a strong correlation between turbidity and *E. coli* densities, which indicated that this method could accurately predict bacteria levels (Lawrence, 2012). This program is called the BacteriAlert Program and on their website anyone can check the estimated *E. coli* bacterial counts, as well as the last grab sample result taken at two different sites along the Chattahoochee River, in order to make informed recreation activity decisions (USGS, 2018). Other studies have corroborated this relationship, finding that turbidity was significantly correlated to *E. coli* in four different watersheds. These authors suggest that efforts to manage surface runoff and erosion should improve water quality (Huey and Meyer, 2010). Although these studies hope to provide recreational guidance to the public, which is important, they do not address the source of the fecal bacteria nor how we can mitigate this concern.

Bacteria in our local waters is not source limited. Recently, Blount (2015) observed that many studies over the past three decades have pointed towards *E. coli* as an unreliable indicator for fecal contamination, since it has been shown to “establish itself as

a member of microbial soil, water, and plant associated communities" (pg. 5). This "particle associated bacteria" is not easy to differentiate from free bacteria and the costs to sample FIB also hinder the ability of researchers to model FIB concentrations (Nevers and Boehm, 2011). Hence, *E. coli* as a source indicator has proven to be both frustrating and unsuccessful in response to the ultimate land use question. The knowledge provided from Blount's (2015) meta-analysis of *E. coli* studies, which shows that *E. coli* can thrive in soil, potentially changes the viewpoint for the turbidity observations and could instead indicate that during event flow, stirred up sediment in a river or stream bottom increases *E. coli* levels. As a result, the bacterial load increase is not resulting solely from stormwater runoff. However, Blount's (2015) analysis does not identify how *E. coli* establishes itself in soil and whether the adaptations that occur to the organism affect their ability to recolonize a host organism. If sediment-living *E. coli* cannot affect humans and the environment in the same way as non-soil established *E. coli*, then maybe this observation is a moot point. If, however, the effect is the same or even worse, being able to differentiate between these types could help discern the source of the bacteria and how to mitigate its effects. This study also potentially indicates that *E. coli* may not be the best option as a FIB, because aside from being able to observe its presence, researchers are unable to isolate the source, whether point or nonpoint.

It is recognized that sewage contamination from SSOs, CSOs, illicit connections, leaking pipes, and septic tanks are all sources of human fecal pollution in our waters and yet many of the tests being utilized to determine bacteria levels in impaired waters does not differentiate between mammalian types (Sedlak, 2014). Despite the potential threat

from human fecal matter, we analyze and make recommendations based on FC or *E. coli*, which is found in all mammalian fecal matter as well as other species including avian (Ashbolt, Grabow, and Snozzi, 2001). This body of research could indicate that the swimmable recommendations provided from these tests are not reliable. Many recent studies have looked for alternatives to *E. coli* for human specific FIB and there are many different strategies being considered to change the way in which we analyze the fecal pollutant load on our local waters. Non-traditional fecal indicators, specific to human excreta are being considered for tracking bacterial movement from land to water. Carson et al. (2005) performed a robust study on Bacteroides thetaiotaomicron and determined that it could be a viable indicator for human fecal contamination as it is mostly found in human excreta, only occasionally found in dog feces, and not found in cow, horse, pig, chicken, turkey, or geese fecal DNA. The EPA is also entertaining alternatives to *E. coli*. In 2015, the EPA published a report that they are considering using coliphages (F-specific and somatic) as viral indicators of fecal contamination in ambient water (EPA, April 2015). There are also many studies being performed to pinpoint the host of fecal matter within a watershed by testing for genetic markers. One such study by Cao et al. (2017) focused on human fecal markers, not just to point out the presence of human fecal matter, but also to determine if that knowledge when applied as a monitoring tool would change the prioritization of remediation efforts. They found that site ranking was completely different based on wet and dry weather results, a nuance of bacterial testing that has already been mentioned as a concern for understanding the land use and bacteria correlation that I seek to explore in my research analysis (Cao et al., 2017). This concern,

along with other complications with bacterial testing, indicates that seeking out ways to reduce runoff in the first place from a planning standpoint is advantageous.

South Carolina: 303(d) and E. coli

In South Carolina, the most recent report for impaired waterbodies was approved for 2016 on June 22, 2017. This document listed *E. coli* as the pathogenic indicator for impaired waterbodies, though some analysis was necessary to establish the transition from FC to *E. coli* (SC DHEC, 2017). The report errs on the conservative side, by establishing the criterion that if 10% of samples are greater than the current standard this indicates an impairment for recreational use and the waterbody should remain on the impaired list. Of the 1,038 impaired waters in South Carolina, 22.37% are impaired due to FC or *E. coli* and in the Saluda watershed, 23.77% of the 122 total impairments are solely *E. coli* (SC DHEC, 2017). Indicator bacteria is the largest impairment in the state of South Carolina (SC DHEC, 2017). South Carolina is not unique in this pollutant concern. According to national data from the most recent state reports (analyzing nearly a third of all rivers and streams), there are approximately 180,000 miles of rivers and streams that are threatened or impaired due to pathogen contamination (EPA, 2017). Within the pathogen category, 89% has been attributed to *E. coli* (58%) and FC (31%) (EPA, 2017). This is problematic as cities plan for their future land uses. If this considerable bacterial volume in our waterways is from an unidentifiable source, then informed decision-making around the health of the waters is limited. Without understanding how bacteria enters our waterways (point vs nonpoint) and from what species (animal vs. human), we will not succeed in solving this murky problem.

Land Use and E. coli

Land use plays a considerable role in determining the effect of stormwater runoff on stream water quality. Increases in impervious surface not only lead to increased pollution load and debris, but also escalates water volumes (two to five times more) and velocities that enter local waterways (Sedlak, 2014). These increases can also lead to erosion concerns and habitat destruction for macroinvertebrates and vegetation. Schiff and Benoit (2007) supply an overview of many studies that showed that as little as a 5% total impervious area increase within a watershed can cause an impairment. Collectively, these symptoms, which result from land use changes and decisions have been described as the “urban stream syndrome” (Walsh et al., 2005). This new terminology is used to describe a long-standing problem in urban land planning. A half a century ago, Leopold wrote a circular for the U.S. Department of the Interior in 1968, before the installment of the CWA, about the hydrological effects of urban land uses.

> *“Land use in all forms affects water quality. Agricultural use results in an increase of nutrients in steam water both from the excretion products of farm animals and from commercial fertilizers. A change from agricultural use to residential use, as in urbanization, tends to reduce these types of nutrients, but this tendency is counteracted by the widely scattered pollutants of the city, such as oil and gasoline products, which are carried through the storm sewers to the streams. The net result is generally an adverse effect on water quality. The effect can be measured by the balance and variety of organic life in the stream, by the quantities of dissolved material, and by the bacterial level”*
>
> (Leopold, 1968, pg. 2).

A few decades later after the inclusion of NPSs to the CWA, Neary, Swank, and Riekerk (1989) noted that the six main sources of NPS pollution were mostly related to land uses: “agriculture, silviculture, mining, construction”, “urban activities”, and “atmospheric deposition” (pg. 2). They also noted that in the southern region, agriculture

was “by far the most pervasive” NPS pollutant, while the rest on the list were noted as more localized concerns (Neary, Swank, and Riekerk, 1989, pg. 2). The EPA in 2006 cited five major pollutants from both point and NPSs to be pathogens, metals, excess nutrients, sediment loading, and organic enrichment (Keller and Cavallaro, 2006). All of these can come from agriculture, which according to the most recent EPA inventory is second only to “unknown” as the most probable source of impairments in assessed rivers and streams (EPA, 2017). Today, agriculture is the probable cause of over 130,000 miles of threatened or impaired rivers and streams (EPA, 2017).

Unfortunately, even with the above knowledge, we are just recently beginning to put serious effort into understanding this relationship. Both attempts to bridge the gap between land use and water quality as well as proposed mitigation methods to minimize the entry of pollutants in our local waterways are currently being discussed. In addition to this work, there has been a resurgence of literature around the phenomenon of a first flush. As noted in a report by the United States President’s Science Advisory Committee Environmental Pollution Panel in 1965, “In the absence of facts it has generally been supposed that the first flush of runoff swept the drains and that flows from the latter part of storms carried less foreign material” (pg. 160). This report goes on to say that the likelihood of this generalization being correct is similar to that of being incorrect (United States President’s Science Advisory Committee, 1965). Three and a half decades later, in 2001 the University of Alabama collaborated with the Center for Watershed Protection to create a National Stormwater Quality Database and the first iteration of this work was published in 2004 (Maestre and Pitt, 2005). By then a definition for first flush had been

determined and a significant first flush became commonly known as one that sees at least "80% of the total pollutant mass" being "transported in the first 30% of the volume discharged during rainfall events" (Bertrand-Krajewski, Chebbo, and Saget, 1998, pg. 2341). Around this time multiple studies were underway to study the first flush phenomenon. Even though this phenomenon has been observed with other contaminants in Maestre and Pitt's (2005) study as well as many others, this has not been statistically significant for FIB (Rowny and Stewart, 2012; Krometis et al., 2007, Stumpf et al., 2010). In some cases, longer rain events have been shown to exhibit an "end flush" due to failing wastewater systems, with the peak FIB concentrations occurring at the end of a rain event (McCarthy, 2009). Hathaway and Hunt (2011) observed the same end flush behavior in NC. McCarthy (2009) observed different results at the four catchments that he was studying and noted that this could be linked to differing sources for *E. coli*, again noting how difficult it is to create a nexus between water quality and land use when bacteria is the topic of concern. Locations that did produce "first flush" behavior could be "sourced…from subsurface origins (e.g. wastewater intrusion)" but they could also be from "surface origins (e.g. domestic and wild animal depositions)" (McCarthy, 2009, pg. 2754). In the North Carolina study, Hathaway and Hunt (2011) also discuss the impact of land use, specifically pervious areas, such as residential yards with domestic animal fecal matter, which could be affecting bacterial concentrations near the end of the storm. Understanding the difference could be critical to pinpoint to then choose the most efficient mitigation effort(s). McCarthy (2009) also raised the notion that a new method is needed to accurately evaluate first flush phenomena for *E. coli* in urban stormwater,

which indicates that revisions to our current sampling methodology may be needed to better inform land use policy.

Other recent studies have taken a targeted approach to correlate land use and FIB with statistical significance. In the coastal southeastern U.S., many forested watersheds are converting to suburban and urban land uses, leading to observable water quality concerns, specifically FIB, most notably in first order streams (DiDonato et al., 2009). In Hawaii, Goto and Yan (2011) observed significantly higher concentrations of FIB in urban stream areas compared to forested reaches of the Manoa Stream. Nash et al. (2008) found that urban and agricultural land uses were the leading causes of enterococci exceeding the standard threshold in the Willamette Valley of Oregon. O'Driscoll et al., (2010) performed a comprehensive research analysis on the studies recently conducted in the southern U.S. They found in Wilmington, NC that the percentage of impervious surfaces within that watershed explained "95% of the variability in average fecal coliform abundance" and in Georgia, all 21 of the urban streams studied there exceeded WQS for FC (O'Driscoll et al., 2010, pg. 625-6). Rowny and Stewart (2012) found that more developed watersheds within NC had higher concentrations of FIB. They focused primarily on inland waters, which is significant for my research since a similar land use correlation was the study's primary goal. The existing research reveals that although land use correlation to water quality is both observed and prevalent across different environments, pinpointing the cause of the bacteria is much more complicated. Even without a thoughtful response to this conundrum, there are many proposed solutions to high bacteria concentrations, which will be discussed below. What is apparent is that

more developed land uses and land cover categories generally lead to elevated levels of bacteria in the water. I examined whether a similar trend could be observed across different watersheds in Greenville County that have different land cover characteristics. Some of the available data also includes wet and dry weather sampling conditions, which have been found to be strongly correlated to bacteria almost to the point of diminishing the land cover effect on bacterial loadings. This aspect of the sampling is more fully engaged in the analysis presented below (see **Chapter 3**).

A Change in Infrastructure Approach: Low Impact Development

In 2015, the Congressional Budget Office (CBO), released a report analyzing transportation and water infrastructure spending from 1956 through 2014 (CBO, 2015). This report notes that aside from a decade long push after the passing of the CWA to address water infrastructure concerns, which focused on building and upgrading sewage treatment plants, federal spending has been roughly an 80/20 split between transportation and water (CBO, 2015; Sedlak, 2014). The 1980s marked a shift with spending during the Regan administration, when an increase in state responsibility for water projects became a necessity as federal funding decreased (Gerlak, 2006). Funding for large projects geared toward correcting major pitfalls within our water infrastructure is simply not available for short term correction and because of this, low impact development design approaches are increasingly popular because of their affordability (Sedlak, 2014). Clary et al. (2008) performed a comprehensive study of Low Impact Development (LID) BMPs, from the International Stormwater Database. From those data sets, they revealed that both media filters and retention ponds show “potential promise in reducing bacteria

counts" (Clary et al., 2008, pg. 6). Even though this data set is substantial in size, all other BMPs did not have enough data to provide statistically significant results for bacteria mitigation. Section 319 requires that BMPs be identified, programs to implement BMPs be put into place, "and a schedule of annual implementation milestones" all get added to the "management program proposal" for NPS (Zaring, 1996, pg. 526). This protocol is beneficial, but only if the efficacy of the BMPs are well understood. Essentially, a group working with a Section 319 grant could waste funds allocated for installments and improvement on BMPs that do not even work or are illogical for their location or pollutant of concern. Also, BMP success may rely on both the nature of the BMP and its implementation. It has been shown that BMP implementation efficacy partially relies on both targeted and individual education (Genskow and Wood, 2009), though there has been some scholarly debate as to the effectiveness of these efforts (Campbell, Koontz, and Bonnell, 2011). I would argue that public education, a topic that will be discussed briefly, due to the more focused land use component of this project, is a critical component of any BMP implementation success. The EPA publishes Section 319 "Success Stories" and they often cite education as a key component (EPA, "Nonpoint Source Success Stories", 2017). Education includes targeted home and farm owner education as well as general public and other stakeholder education (EPA, "Nonpoint Source Success Stories", 2017). In rural areas, where agricultural land uses lie near waterbodies, BMPs can lead to "reductions in chemical runoff and soil erosion that would otherwise pollute waterways (Campbell, Koontz, and Bonnell, 2011, pg. 1128). Finally, seasonal variation can cause another complication in terms of BMP success (Pan and

Jones, 2012). More studies need to be engaged to determine the effectiveness of these BMPs. It also appears advantageous to work locally on these efforts since the effectiveness of certain BMPs could vary by location.

One region that has taken an innovative approach to the BMP conundrum is the City of Charlotte, NC and Mecklenburg County, NC. Their attitude is that proprietary BMPs are ineffective unless proven otherwise. The city does not “approve the general use of proprietary structural SCMs [Stormwater Control Measure] and/or innovative SCM designs to meet stormwater quality and quantity treatment requirements” unless they meet the requirements of their pilot program (Pilot SCM Program, 2017, para. 15). This a cautious, but also thoughtful approach due to the lack of significant research available on some of these BMP strategies. It is also apparent that if BMPs are not maintained, like anything else, they will fail to perform in the manner in which they were designed. Rather than allowing developers or property owners to check off the BMP box by stating that they are implementing inlet filters, for example, this strategy forces a more thoughtful conversation to meet water quality and quantity standards and keeps the protection of water at the forefront and localized. This program is organized by the County stormwater services and is part of the Water and Land Division of the Mecklenburg County Land Use and Environmental Services Agency. The overall goal of this program is to “evaluate various types of structural stormwater control measures…within different land uses to determine their best use and effectiveness within Charlotte-Mecklenburg’s overall stormwater management program” (Pilot SCM Program, 2017, para. 2). This work then allows them to consider these control measures

for their BMP Design Manual, which they decide based on capital cost, operation and maintenance requirements and costs, pollutant removal efficiency and effluent quality, and stormwater quantity control capabilities (Pilot SCM Program, 2017).

A Change in Infrastructure Approach: Green Stormwater Infrastructure

Another example of more natural mitigation strategies is Green Stormwater Infrastructure (GSI), which is a subset within the greater topic of Green Infrastructure (GI) and was lauded by the EPA as both a "cost effective and environmentally preferable approach to reduce stormwater and other excess flows entering combined or separate sewer systems" (EPA, 2007). GSI is defined by Chini et al. (2017) as "infrastructure that utilizes natural processes such as infiltration to reduce, slow down, and clean runoff (e.g. green roofs, bioswales, rain gardens, and permeable pavement) (pg. 3). Gray infrastructure is the term used to refer to traditional stormwater engineering, which uses concrete pipes to remove stormwater quickly (Chini et al., 2017). Often there is a misconception that doing anything "green" automatically leads to higher costs, however many studies including ones in Maryland and Illinois showed that new residential developments using GSI controls "saved $3,500 to $4,500 per lot (quarter to half-acre) when compared to new developments with conventional stormwater controls (Kloss and Calarusse et al., 2006). When it comes to GSI planning it is critical to understand that the rules are not firm and there is flexibility and customizability for implementing these technologies (Chini et al., 2017). One GSI method, biofilters, have been shown to be an effective strategy for both the removal of as well as antibacterial activity against fecal microorganisms (Chandrasena et al., 2017). Benedict and McMahon (2006) have

highlighted ten principles for success that may be used as benchmarks for planning new efforts or strengthening existing ones. Many of the same principals can be applied to stormwater specific infrastructure (see **Table 1** below). Principles 1 through 4 and 7 through 10 should be considered as written for stormwater, replacing the GI with GSI. Principles 5 and 6 could be adjusted. In many cities across the country, aging gray infrastructure is already in place and causing major problems in terms of leaking pipes, CSOs, SSOs, and illicit connections. These places do not have the luxury to plan prior to development; although they could apply these to new development. Principle 5, could thus have a critical caveat encouraging cities to work on replacing the current gray infrastructure with green principles. This also relates to similar changes to principle 6: GSI is a critical public investment that should be funded up front for new development and should be a funding priority when cities plan for upgrades to the current system.

Table 1: Ten Principles of Green Infrastructure

Ten Principles of Green Infrastructure (GI)
1. Connectivity is key.
2. Context matters.
3. GI should be grounded in sound science and land-use planning theory and practice.
4. GI can and should function as the framework for conservation and development.
5. GI should be planned and protected before development.
6. GI is a critical public investment that should be funded up front.
7. GI affords benefits to nature and people
8. GI respects the needs and desires of landowners and other stakeholders.
9. GI requires making connections to activities within and beyond the community.
10. GI requires long-term commitment.

Source: Adapted from Benedict and McMahon (2006)

It is crucial that as we plan for the future, thoughtful and strategic decisions must be made around land use choices to lessen the impact of fecal bacteria on our nation’s

waterways. Also, even though the CWA treats pollutants separately, scientifically pollutants enter the waters all together through stormwater runoff. Land use decisions that benefit the reduction of a single pollutant on a water network, could very well also benefit the other pollutants traveling with it and we need to continue to think in this holistic, one water manner.

Literature Summary: Motivation for Thesis Study

The CWA lacks firm regulation by which to control NPS pollution, leaving this power at the local level, in the hands of the state. This results in inconsistent mitigation practices and different standards for pollutant loads across the U.S. Bacteria from NPSs is clearly evident in the literature from both developed and agricultural land uses, but solutions for this widespread problem are lacking and not well understood. This includes both simple policy regulations, such as buffers, and GSI and LID BMP strategies directed at bacteria mitigation. Also, the literature discussing soil dwelling *E. coli* strains is light, which is a potential gap in the understanding of NPS bacteria pollution and land use.

Bacteria is a fickle parameter that is challenging to predict and the corresponding land use types are equally difficult to correlate to the diffuse bacterial sources within local waterbodies. Even with the vast literature explaining the complication of correlating bacteria with land use, *E. coli* as a parameter has been and continues to be utilized to inform health risks related to recreational activity. Up until 2013, SC used FC as an indicator for fecal pollution, but today the WQSs are measured with *E. coli* as the parameter (SC DHEC, 2017). *E. coli* is a gram-negative rod that is found commonly in warm-blooded animal intestinal tracts and can indicate the presence of disease-causing

pathogens (Harmon, West, and Yates, 2014, WHO, 2018). It is important to remember that the presence of *E. coli* indicates that fecal contamination exists, but it does not indicate the bacterial source nor the health risk.

The lack of understanding around first and end flush as it pertains to *E. coli* and the impact of weather conditions during sampling are another facet of confusion for this topic. Finally, it appears that although the relationship between bacteria and land use is being engaged in the literature, how it affects land use planning is a gap this study sought to address. It is one thing to pinpoint the source, but being able to inform land use change that can act as mitigation or even prevention during the current development growth trend in Greenville County is critical. Using local data for *E. coli*, I considered if a correlation could be made between urbanized land cover and land uses and *E. coli* levels in Greenville County, and if so, how land use policy could better address this relationship. By engaging this topic, a better understanding of land use policy recommendations could result, potentially impacting both ecological and human health. The following research design, focusing on *E. coli* data within Greenville County, was assembled to reveal the effectiveness of these strategies in informing land use policy recommendations (see **Chapter 3**).

E. coli Prediction A Multiple Regression Model Analysis

The goal of this research was to look at the existing data within a region, Greenville County, and to analyze the data for land use correlations to *E. coli* levels within the local waters. The work being completed for the Section 319 grant with the Reedy River has opened up the conversation for key stakeholders about improving water

quality. It is the hope that this study further sustains these water quality improvement efforts with collaboration between the City and County of Greenville. Using a multiple regression analysis, I answered the following question: was there a correlation between urbanized land cover and land uses with *E. coli* impairments in Greenville County? And if so, how might land use planning policy address this relationship?

CHAPTER THREE: RESEARCH DESIGN, METHODS & ANALYSIS

Introduction

The intent behind engaging a case study within this research is to satisfy the twofold technical definition of a case study according to Yin (2009). This inquiry will both "investigate a contemporary phenomenon in depth," trying to shine light on this topic, as well as attempt to bridge the boundary "between phenomenon and context", since they are not clearly evident (Yin, 2009, pg. 18). The objective of this research design is to examine available bacteria water quality data from three sources within Greenville County, South Carolina and determine land use policy recommendations at this critical moment in planning for future growth and development within this region. The first data set is publically available data published by the EPA, USGS, and USDA on their water quality portal site and performed by SC DHEC (National Water Quality Monitoring Council, 2018). The second and third sources are localized private sampling efforts that were performed at the County and City level in Greenville. The specific land use policy recommendations that should result from this study are land use conversion or protection recommendations and buffer requirements to help mitigate the effects of bacteria on the local waterways.

Explanation of Research Design and Method

Greenville County is located in Upstate SC. The County boundary lies within four Hydrologic Unit Code (HUC) 8 designations, the Saluda River (03050109), Enoree River (03050108), Tyger River (03050107), and Upper Broad River (03050105), though the sampling locations lie only in the first three HUC 8 locations. These watersheds offer

certain characteristics that provide motivation for this case study. First and foremost, the top portion of the Saluda Watershed, which is also the top most portion of Greenville County, embodies specific features that provide a critical component for this analysis. This area, considered the headwaters of the basin, is a pristine and highly protected area. Both the North Saluda Reservoir and Table Rock Reservoir are not open for recreation and they provide drinking water to the Greenville area via Greenville Water Utility Company. These areas, along with the local streams and creeks drain south, first passing by rural land uses and then towards urbanization, beginning with Travelers Rest and then moving south to the City of Greenville. After Greenville, the streams and rivers meander further to Lake Greenwood and further still to Lake Murry at the bottom of the Saluda watershed. The changes in water quality as land uses vary have been extensively studied, especially within the Reedy River by both public and private entities, though a focus on *E. coli* in this manner has yet to be accomplished. Both the City and County data are located along the main stem of the Reedy River, which is a main focus within this case study.

The Reedy River has been a focal point for the community surrounding it and a natural source for industry since the 1770s. During the summer of 2017 the EPA approved the previous year's SC Integrated report for Section 303(d) List of Impaired Waters. Within this report, the Reedy River is listed as impaired in various sections for *E. coli*, Hydrogen Ion Concentration (pH), Total Nitrogen, and macroinvertebrates (SC DHEC, 2017). This same summer also marked the formal introduction of the Adopt-A-Stream program in South Carolina (SCAAS), which was modeled after the Section 319

funded program in Georgia. This program has sparked citizen science interest in the area, which includes awareness of *E. coli* in the Reedy. Media attention has also recently been directed toward this topic and amplified locally, including a mother concerned about her child playing in the stream behind her home (Churches, 2017). The Greenville News published their own sampling for *E. coli* during the summer of 2017 (Conner, 2017) and two local high school students were awarded the Presidential Environmental Youth Award for their citizen science work within the Reedy (McDonald, 2017). Currently the Saluda Watershed has 47 approved TMDLs and all of them are bacteria related (see **Table 2** below). Understanding the implications of these bacteria levels is important for planners. This study comes at a critical time, as growth within Greenville pushes the current infrastructure capacity and increases concern for sprawl in the Charlanta region (which is Greenville, SC, the epicenter of Charlotte, NC and Atlanta, Georgia). Charlanta is continually being mentioned by the media and even in the most recent Greenville City Council Election, fall 2017, every candidate commented about smart growth and thoughtful development. This conversation is well-timed since in May of 2017, the U.S. Census Bureau revealed that Greenville, SC, is the fourth fastest growing city in the nation based on percent change from July 1, 2015, to July 1, 2016 (U.S. Census Bureau, 2017). Also, a 2011 study utilizing the National Land Cover Database (NLCD) revealed that South Carolina saw the third largest impervious surface area change between 2001 and 2006 in the United States at 7.92% (Xian et al., 2011). Finally, economic forces are "reshaping the [southeastern] landscape through urbanization" in an area that has been traditionally rural and contains some of the most productive forests; and for this reason

alone, it is important to monitor this change (Milesi et al., 2003, pg. 401). The land use policies, or lack thereof, that allow these changes to occur are critical to analyze for their effectiveness at mitigating the negative externalities of this growth (e.g. increased pollution loading). Specifically, polices that come from the MS4 permitting process, including buffer requirements, permitting such as NPDES and agricultural permits, zoning, and loose BMP utilization requirements all have the potential to affect bacteria in local waters.

Table 2: Current Approved TMDLs:
HUC 8 Watersheds Greenville County Overlaps

Waterbody	Parameter of Concern	Sites
Big Creek	Fecal Coliform	RS-05590
Broad Mouth Creek	Fecal Coliform	S-010, S-289, S-304
Bush River	Fecal Coliform	S-046, S-102
Little River	Fecal Coliform	S-034, S-038, S-099, S-135, S-297, S-305
Little Saluda	Fecal Coliform	S-050, S-123, S-255, S-290, S-306, S-324
Lorick Branch	Fecal Coliform	S-150
Lower Saluda River	Fecal Coliform	S-149, S-294, S-260
Mill Creek	Fecal Coliform	S-315
Ninety Six Creek and Tribs	Fecal Coliform	RS-03346, S-092, S-093, S-233, S-235
Rabon Creek	Fecal Coliform	S-096, S-307, S-321, S-322
Rawls Creek	Fecal Coliform	S-287
Scott Creek	Fecal Coliform	S-044
Upper Saluda River Basin	Fecal Coliform	S-004, S-005, S-007, S-087, S-103, S-171, S-250, S-252, S-267, S-299, S-300, S-301, S-302
Enoree River*	Fecal Coliform	B-035, B-037, B-038, B-041, B-053, B-054, B-072, B-097, B-150, B-186, B-192, B-231, B-241, B-246, BE-001, BE-007, BE-015, BE-017, BE-018, BE-020, BE-024, BE-039, BE-040
Tyger River**	Fecal Coliform	B-005, B-008, B-012, B-014, B-018A, B-019, B-020, B-021, B-051, B-067A, B-067B, B-164, B-199, B-219, B-235, B-263, B-286, B-287, B-315, B-321, B-332, B-336, BF-007, BF-008
Upper Board River Watershed***	Fecal Coliform	B-026, B-028, B-042, B-044, B-048, B-056, B-057, B-059, B-062, B-088, B-095, B-100, B-103, B-119, B-126, B-128, B-133, B-159, B-191, B-211, B-221, B-259, B-277, B-278, B-301, B-302, B-323, B-325, B-326, B-330, B-331, B-334, BL-001, BL-005, BP-001

Source: SC DHEC, 2017 *Approved TMDLs By Watershed.* Accessed on November 15, 2017. Retrieved at http://www.scdhec.gov/HomeAndEnvironment/Water/ImpairedWaters/WatershedAreas/#saluda

Note: All of the above are from HUC designation 03050109, the Saluda Watershed unless otherwise denoted below

* = HUC 03050108

** = HUC 03050107

*** = HUC 03050105

Currently the other three watersheds, which the boundaries of Greenville County fall within, Enoree River (23), Tyger River (24), and Upper Broad River (35) also have approved TMDLS (total number next to the watershed), all of which are bacteria related (see **Table 2** above). These watersheds have less defined land use transitions from the headwater to the discharge point within Greenville County, yet provide different land use coverage in comparison to the Reedy River sampling points.

Current Policy: Greenville County Discussion

Beginning with the 2002 Section 303(d) list reporting cycle, the U.S. EPA's Integrated Report Guidance "recommends that States use five" categories "to report on the water quality status of all waters in their State", as listed below (Monschein & Reems, 2009, pg. 779).

- *"Category 1: All designated uses (DU) are supported, no use is threatened;*
- *Category 2: Available data and/or information indicate that some, but not all of the DUs are supported;*
- *Category 3: There is insufficient available data and/or information to make a DU support determination;*
- *Category 4: Available data and/or information indicate that at least one DU is not being supported or is threatened, but a TMDL is not needed;*
- *Category 5: Available data and/or information indicate that at least one DU is not being supported or is threatened, and a TMDL is needed."*

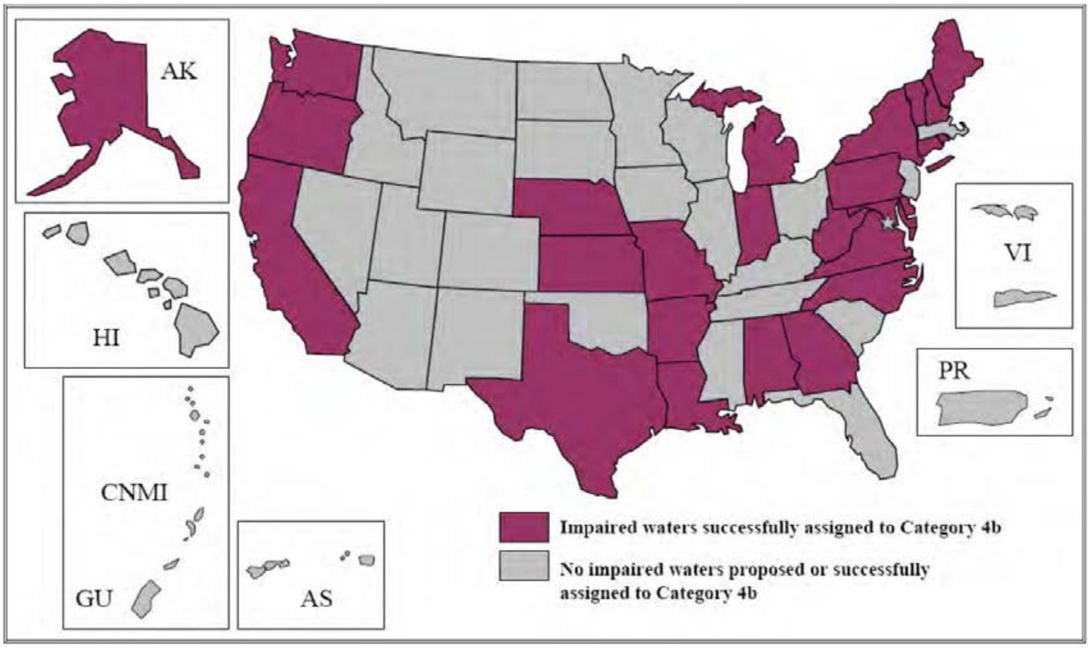
(Monschein & Reems, 2009, pg. 779).

Category 4 and 5 indicate that a waterbody is either impaired or threatened. A further breakdown of Category 4 is as follows. Category 4a waters indicate a TMDL has been completed, a category 4b designation indicates a TMDL is not needed because there are "other pollution control requirements" that are expected to reach attainment of the WQS

within a “reasonable period of time”, and the category 4c designation denotes a waterbody that will not attain the WQS because the pollution “is not caused by a pollutant.” (Monschein & Reems, 2009, pg. 779). An example of this final category is a waterbody impaired solely by inadequate flow or by stream channelization (Monschein & Reems, 2009).

Category 4b strategies are still minimally utilized and yet, according to the most recent study performed by the EPA in 2009, 26 states have assigned over 400 waterbodies to category 4b strategies (Monschein & Reems, 2009). This was a notable increase from a 2006 survey in which only 15 states were utilizing category 4b strategies on 267 waterbodies (see **Figure 2** below) (Monschein & Reems, 2009). Minimal discussion of category 4b strategies currently exists within the literature and the success of these strategies is not well documented. With respect to South Carolina, they have not yet proposed or successfully assigned a category 4b waterbody (Monschein & Reems, 2009). The lack of communication and understanding around these alternatives could explain their minimal utilization. Also, there is a gap in the literature engaging TMDL success versus category 4b approaches. A similar theme is also true for Category 5 waters, which is a critical strategy present within my case study, discussed further below.

Figure 2: Category 4b Prevalence in the United States, May 2009



<u>**Source:**</u> Monschein, E.; Reems, S. (2009) *Category 4b – Current National Status and Trends.* Retrieved from US EPA: Office of Water service website: https://www.epa.gov/tmdl/category-4b-national-status-and-trends

The Reedy River, which one third of my sampling sites are located, is categorized as impaired under the EPA 303(d) list and became a Category 5 water beginning in 2015 (personal communication, City of Greenville, March 26, 2018). Specifically, it is referred to as a 5R category water where the R stands for "restoration", and with this designation includes an alternative restoration plan that is predicted to restore the waterbody without the implementation of a TMDL (City of Greenville, personal communication, November 20, 2017). The benefit of this type of program is that it allows those with the most local knowledge about the river to work towards its betterment and exercise informed judgement based on proximal knowledge. The EPA recognizes that the TMDL process, which is a calculated approach to water quality mitigation, may not always be the most

efficient way to reach water quality standards. In 2013, the EPA released a new framework for 303(d) waters and specific program responsibilities, entitled "*A Long-Term Vision for Assessment, Restoration, and Protection under the Clean Water Act Section 303(d) Program*" (EPA, 2013). The implementation of a pilot 5R program, which was first tested in EPA Region IV, allows states to take a watershed-based approach to meet water quality standards. A TMDL must be developed if the proposed plan does not succeed, but is not mandatory otherwise (City of Greenville, personal communication, November 20, 2017). The primary stakeholders responsible for the Reedy River water quality regulatory requirements were granted the opportunity to develop an alternative restoration plan that was specifically focused on nutrients, nitrogen and phosphorus and chlorophyll a (City of Greenville, personal communication, November 20, 2017).

Spurred from this pilot program opportunity, local organizations, including the City and County of Greenville, formed what is called the Reedy River Water Quality Group (RRWQG), whose prime goal is to develop this alternative plan using adaptive management strategies (discussed above). Within this goal is the overarching strategy to come up with the best ways to keep potential sources of pollutants within the watershed out of the local waterways. The group is currently organized into five committees to help see this process through. I have been fortunate enough to partake in the Public Outreach Committee and have learned the challenges of bridging the education gap around water quality while balancing transparency with general understanding. According to the RRWQG's most recent report, "the Reedy River arm of Lake Greenwood and Boyds

Millpond are no longer impaired by total phosphorous and chlorophyll a (algae)" (RRWQG, 2016, pg. 2). This document also indicates that this past year (2017) the group has worked towards identifying BMPs that will best benefit this local region (RRWQG, 2016). They are considering "landscape activities, prohibitions of practices, maintenance procedures, treatment requirements, and other management practices to prevent or reduce the pollution of waters of the United States" (RRWQG, 2016, pg. 6).

Before the 5R designation, both the City and County of Greenville performed routine sampling for nutrients and *E. coli*. The purpose of the bacteria sampling at the City was at the request of City Council to monitor bacteria levels during major sewer upgrades in 2012 and 2013 and the sampling continued and is still being collected, though less frequently. The bacteria data is currently being discussed and analyzed for the purpose of aiding in public education, though no documents have been published on this topic as of yet.

Prior to these efforts there was a document published in 2012 that engaged the land use water quality nexus in the Reedy, but it glazed over fecal bacteria, simply stating that pasture land is prone to high nutrient runoff due to livestock fecal matter (Privette et al. 2015). Prior to the 5R efforts, there has not been a widespread watershed approach for dealing with FIB pollution. The City and County of Greenville are also permitted under MS4 permitting. The MS4 permitting process is an important policy component to discuss as it relates to this case study. This amendment to the CWA in 1987 was established to regulate stormwater discharges. Both large (urban population exceeding 250,000) and medium (urban populations between 100,000 and 250,000) were required to

maintain permits for their stormwater discharges beginning in 1990 (Phase I), while smaller locations, referred to as small MS4 (populations greater than 10,000) began in 1999 (Phase II) (Maestre and Pitt, 2005; Hardy & Koontz, 2007). Both Greenville County and the City of Greenville operate under MS4 permitting processes. This regulation includes the requirement to maintain a stormwater management plan. There are a few key components that are important to highlight with respect to this project, which will be identified below in **Table 3**. This regulation falls under the environmental engineering departments for both the County and the City of Greenville.

Table 3: Greenville County and City of Greenville Water Quality Policy Summary

Policy Land Use Description	Greenville County[1]	City of Greeville[2]
Buffers	**Filter/Buffer Strip:** Minimum length of 15 to 20 ft.	**Linear Buffers:** Watersheds If >20 acres and <1 mile = 30 feet on each side of the channel; If > 1 mile = 50 feet on each side. **Waterbody buffers:** total SA If > .10 acre and <1 acre = 30 feet; If ≥1 acre and <2.5 acres = 40 feet; If ≥2.5 acres = 50 feet
Impervious Surface Water Quantity Requirements	Stormwater detention is required though waivers are available for in-lieu fees, though these can be waived with LID implementation. No downstream impact must be proven in application	Water quantity is required when the development creates more than 0.25 acres of new impervious surfaces.
Impervious Surface Water Quality Requirements	Size permanent water quality capture devices to trap 85% of total suspended solids (TSS) based on annual loadings. Or a device may be sized to capture the first inch of runoff from the impervious area of the site and discharge it over a 24 hour period	If development creates a new impervious surface greater than or equal to 0.25 acres, water quality is required. Hydrocarbon removal technology shall be required for all areas accepting flow from parking/loading areas, and vehicle drive surfaces (e.g. roadways and driveways). The volume for hydrocarbon removal shall be based on 0.5 inch over the impervious surfaces described above to each treatment device. The Hydrocarbon removal rate shall be a minimum 50 percent. The volume for Hydrocarbon removal shall not be in addition to those volumes calculated for other water quality, provided the method of treatment provides a hydrocarbon removal rate of 50 percent.
State Law	Permanent water quality infiltration practices shall be designed to accommodate at a minimum the first 1-inch of runoff from impervious areas located on the site.	

Notes & Source:

Both the City and County charge a fee for stormwater

[1] Greenville County (2013) *Greenville County Storm Water Management Design Manual* Retrieved from https://www.greenvillecounty.org/LandDevelopment/pdf/designmanual/DesignManual_revJan_2013.pdf

In this document the County does provide many ideas to reduce CN number (impact of increased impervious with development, which also comes with additional cost).

[2] City of Greenville (2014) *The City of Greenville Stormwater Management Plan (SWMP)* Retrieved from https://www.greenvillesc.gov/DocumentCenter/View/1157

A major permit is required if the increase in impervious surfaces is greater than or equal to a ¼ acre.

Both the City and the County also must comply with permitting and restrictions by SC DHEC. This study chooses to look at two specific policies that specifically can lead to fecal contamination in Greenville County waters; agricultural permits and NPDES permits. NPDES permits were discussed in **Chapter 2**, though for South Carolina it is important to note that the standard is the same throughout the state for all discharges to waterbodies of the state at a maximum monthly average *E. coli* level of 126 MPN per 100 ml or a daily maximum of 349 MPN per 100 ml (SC DHEC, 2017). For the agricultural permits, the State allows the spreading of animal manure, also called land application. This is not to be confused with CAFOs, which directly discharge wastewater into a waterway (USDA, n.d.). The South Carolina regulation 61.43 does not allow this type of discharge, essentially making it illegal to have a CAFOs in SC. The way in which this is tracked at the state level makes it difficult to correlate exactly where placement of the manure is occurring versus whom owns the actual permit. Some places broker their own manure, a theme becoming common with poultry farmers (personal communication, SC DHEC, February 12, 2018). The details for both of these permits will be presented below in the *Data Gathering Strategy: Fecal Bacteria Related Permitting* Section.

The growth trends, notoriety of the bacterial contamination, and the lack of knowledge correlating *E. coli* and land cover or land use in this watershed, demonstrate the contemporary nature of this topic, which Yin (2009) states is a critical aspect of case study research design. Sufficient access, which is another critical aspect to case study research was another characteristic used to choose this case study (Yin, 2009). The water

quality data, specifically for bacteria were available for academic research from the City and County, as well as the EPA.

Data Gathering Strategy: E. coli

E. coli samples were gathered from all available entities within Greenville County. Sub-watersheds were delineated using ArcHydro and the land cover and land uses characteristics within each boundary were determined spatially using ArcGIS. NAD 1983 HARN South Carolina State Plane (international feet) was the projection used for all analyses. R statistical software was utilized to assess all relationships between *E. coli* and land cover, land use, and permitting, within this study (R Development Core Team, 2010). The approaches for each component are discussed in greater detail, below.

Varies entities have collected water quality samples from Greenville County waters within the various sub-watersheds inside or near the political boundary. The purpose of the sampling varies by entities, but generally pertains to fulfilling an EPA or SC DHEC requirement. At the onset of this study, I contacted all known water quality concerned entities including counties, cities, Non-Governmental Organizations (NGOs), and private corporations to inquire about *E. coli* data availability. All entities were also asked for referral entities, which I followed up on to ensure all possible data venues were engaged. Finally, I reviewed and then retrieved publicly available data from SC DHEC and the EPA. A summary of these entities and their data are included in **Table 4**. Three different bacteria sampling data sets were chosen for this study, including the EPA and SC DHEC data (2009-2017), the City of Greenville data (2012-2016), and Greenville County data (2010-2016). I chose the City and County data because the jurisdictions

proactively sampled for bacteria, their sampling sites were consistent, and each sample came with the corresponding sampling condition differentiation of either wet weather or dry weather, which is something the SC DHEC data did not specify. I chose the SC DHEC data because of the extensive nature of the data set throughout the County and its public availability. Anyone seeking information on this topic, whether it be a local government agency, municipality, NGO, or citizen can access the EPA water quality data (National Water Quality Monitoring Council, 2018). The Adopt-A-Stream program did not have an extensive data set and the laboratory process is completely different from the other methods, making these data incompatible with the other data sets. These data may prove more valuable for SC and planning if the program gains the same popularity as Georgia.

Data received by Greenville Water were not considered for this study due to the sampling methodology. Greenville Water samples are at the intake valve at each reservoir meaning that these sampling points are not surface water samples. The North Saluda Reservoir intake is between 20’ and 35.5’ below water surface, while the Table Rock intake is between 25’ and 45’ below water surface, rendering these data incompatible in comparison with surface water data (Jeff Czarnecki, personal communication, October 9, 2017). Aforementioned, the *E. coli* standard is a maximum monthly average *E. coli* level of 126 MPN (most probable number) per 100 ml or a daily maximum of 349 MPN per 100 ml (SC DHEC, 2017). Of the data made available to me from Greenville Water for this study, none of them came close to exceeding that standard, as would be expected in this highly protected head water.

Data provided by Renewable Water Resources (ReWa) were mostly effluent samples taken before the discharge enters the river and many locations, due to older NPDES permits, are currently testing FC and not *E. coli*. The current SC DHEC standard for FC is 200/100mL (SC DHEC, 2017). These data did have one pre and post effluent surface water sample from the same day that showed it was three times more likely for the pre sample to be greater than the post sample, indicating that the effluent discharge could have been diluting FIB samples at that location and the purpose of the permit is effective, though since these data were not engaged, this notion is purely speculative. During the same time frame, mid 2013 through the beginning of 2017, the highest FC level from the effluent was well below the SC DHEC FC standard.

Table 4: Summary of Greenville County Bacteria Data Availability by Entity

Entity	Data (years)	Location	Public/ Private	Willingness to Share
SC DHEC	2009-2017	Saluda Watershed	Public	Yes, data is publicly available https://www.waterqualitydata.us/portal/
Greenville County	2010-2017	Within County Boundary, plus one downstream location	Public & Private (*E. coli*)	Yes: http://gcfieldnet.woolpert.com (for the public data) Username – reedy5r Password – reedy5r
City of Greenville	2012-2017	City limits	Public & Private (*E. coli*)	Yes: http://fieldnet.woolpert.com (for the public data) Username– citypublic Password – public
ReWa	2005, 2013-2017	Within the company locations	Private	Yes
Greenville Water	2012-2017	North Saluda & Table Rock Reservoirs	Private	Yes

After narrowing the above data to the study area of Greenville County and *E. coli* only sampling, the resulting data for this study were comprised of 26 SC DHEC sampling locations with 611 individual sampling events and eight City/County locations with 631 individual sampling events. All locations after being properly projected onto SC State Plane, were cross checked for proper location. All sampling events came with a grab sample *E. coli* level and sample time and date. The City and County data included additional information that was considered within this study, which is the differentiation between wet and dry sampling conditions. Wet versus dry conditions do not simply indicate the presence of a storm event during sampling (i.e. rain, snow, ice, etc.).

Woolpert, a national consulting firm, performed a complicated analysis for the City and County of Greenville, which included separating storm events from time-series hydrographs. Woolpert's storm analysis tool incorporates a digital filter signal processing algorithm that is utilized in Purdue University's Web-based Hydrological Analysis Tool (WHAT). Input parameters, unique to each of the City's and County's watersheds, are specified to determine the portion of a time-series hydrograph (continuous data collected by the City and County) that should be considered baseflow versus stormflow or dry weather versus wet weather, depending on the intended application of the tool. This method of storm event separation removes subjectivity and is a fast, reproducible, and consistent tool, but it has no physical meaning (Lim et al., 2005). Due to both time and cost, this analysis was not available for the SC DHEC data.

Also notable for this data set is of the 34 locations, nine are lake locations, while the other 25 are stream locations. Within this data set, ten of the locations are along the main stem of the Reedy River, ten drain to Lake Robinson in Greer, SC, and the remaining 14 locations are located throughout the county and represent areas that are the most forested, have the highest agricultural land, and the most urbanized land cover within the study watersheds. They all add both more data for this analysis, but also diversity in the type of land cover and land use drainage area, which is helpful for creating a more thorough model. A visual demonstration of the locations for this study is provided in **Figure 3**.

Figure 3: Sampling Locations and Study Area Watersheds

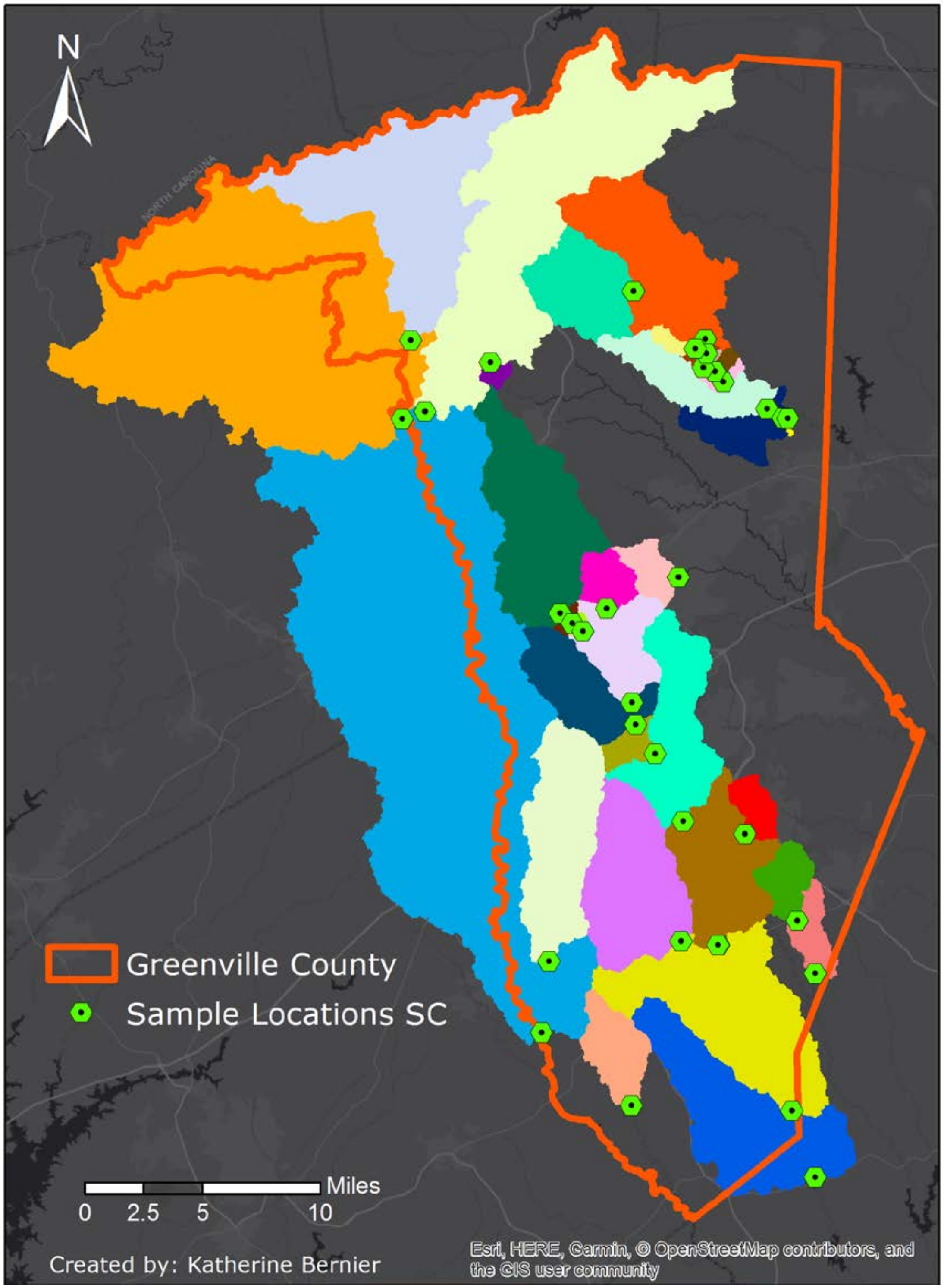


Figure 3: Sampling Locations and Study Area Watersheds (cont).

<u>**Note:**</u> The above names are given based on the sampling location for this thesis and are not names of official HUC designated watershed.

It is important to note the *E. coli* measurements retrieved from all the above entities are not a complete picture. They were all collected as grab samples and show only at a given moment in one single location what the *E. coli* level was and alone are not representative of the river as a whole. Due to the nature of the laboratory test to determine bacteria levels and cost of analysis, continuous sampling of *E. coli* is not performed. *E. coli* is also only good for indicating the potential presence of fecal pollution and is not a good indicator for human sewage, since it is not specific to human fecal matter. Water samples that are to be tested for FIB often need to be distributed to the lab within 12-24 hours of sampling and require a 24 hour incubation time before

determining the result. Genetic specific testing for FIB exists, but it is expensive, often ranging between $300-500 per test, which is well beyond a municipality budget.

The available data showed that the majority of the sampling events produced a measurable amount of *E. coli*. As mentioned above, standard routine monitoring of *E. coli* by SC DHEC did not begin until 2013, hence the data available prior to 2013 from the water quality portal is the result of special studies that were performed to determine the best indicator and level to set the standard (personal communication, SC DHEC, February 3, 2018). The City and County data have all been in the same locations during the whole study period. Of the total *E. coli* samples (1242) analyzed within this study, there were very few censored data, with 23 being above the quantification limit, seven being below the quantification limit, and 3 being non-detects. The quantification limit is a term used interchangeably with the detection limit (DL) for this data set (personal communication, SC DHEC, February 3, 2018). For data sets where the number of below detection limits is low, which for this set it is under 1% of the data, it is customary and accepted to use DL/2 (EPA, 1989; Farnham et al., 2002). For the under 2% of data points that were above the detection limit, the value for the detection limit was used. Each individual *E. coli* sample, which is the response variable for my analysis, was then paired with each chosen predictor variables by year, which will be explained in subsequent sections.

Data Gathering Strategy: Watershed Boundaries

Based on previous studies and the nature of *E. coli* within water, I chose a watershed approach for this analysis. Since *E. coli* does not appear to exhibit first flush,

narrowing the land use to those most proximal would seem to bias the results. The survival rate of *E. coli* in water also supports a broader, more holistic inclusion of all potential drainage areas to the sampling point. There is precedent for using a watershed based approach, as previous research has done so with a similar goal of bridging the land use and bacteria nexus, and it has been a successful strategy for different types of land cover watersheds (Halstead et al., 2014, Mehaffey et al., 2005; and Verhougstraete et al. 2015). Halstead et al. (2014) noticed that areas both near a stream and father away appeared to have "equivalent impacts" on water quality, further motivating a watershed approach rather than using a buffer approach within this thesis study (pg. 3392).

To create watershed boundaries from each sampling point, I used the ArcHydro package within ArcMap. This enabled me to build a boundary upstream of each sampling site that encompassed all possible land cover and land uses (impervious surface) draining to the sampling location. First, I acquired Digital Elevation Model (DEM) data at the best available accuracy for the area from the United States Geological Survey (USGS). Currently, Greenville County and its surrounding area have 1/3 arc-second DEM, which is roughly a 10-meter resolution. I trimmed these data to the study area and projected onto SC State Plane in feet and subsequently the elevation portion was converted into feet, since the default is meters from USGS. I utilized the ArcHydro extension, performing the following processes; sinks were filled, flow direction was determined, flow accumulation was calculated, and stream definition was created. I then converted the streams to a feature. The number of cells used to initiate a stream was 300. I then used the Snap to Pour Point tool within the Hydrology tool set of the Spatial Analyst extension to

delineate a watershed from the 34 sampling locations. The snap distance utilized was 300 after substantial troubleshooting. The smaller the snap distance, the more inaccurate the watershed became and the larger the snap distance, the more downstream land area the tool would include. I also manually tested moving the sampling locations to the center of the delineated stream within ArcHydro, but it did not improve accuracy to the watershed boundary, and so the locations were left as they were provided by SC DHEC and Greenville County and City. For most of the locations, the watershed created was reasonable and the only alterations were the vertices at the bottom near the sampling point. I altered these by hand using the Editor tool and followed the four foot elevation contours, provided by Greenville County. Those that did not result in reasonable watersheds were those adjacent to a small body of water or lake. For those locations I performed a more careful manual correction, again following the four-foot contour lines.

Five of the watershed boundaries spanned beyond the Greenville County border, which did not provide a problem for land cover analysis in terms of the NLCD, but it did affect some of the more detailed analyses, which will be further discussed below. The naming strategy for these watersheds was determined based on the sampling locations and do not pertain to specific HUC watershed designations (see **Figure 3**). Due to the nature of the sub-watersheds created within this study area, it is reasonable to generalize the observations made below to other similar locations, with the hopes of informing the effects of urbanization and specific land uses on *E. coli* levels in our local waters.

Data Gathering Strategy: Fecal Bacteria Related Permitting

I was able to access two additional sources of potential *E. coli* pollution information to further differentiate my sampling points, NPDES permits and agricultural permits; the frequency of which can be noted in **Table 5** and the distribution in **Figure 4**. Both businesses and municipalities are permitted through SC DHEC to discharge sanitary waste into a local waterway through NPDES permits and agricultural permits. I was able to obtain locations and details for both of these categories from SC DHEC, current as of January, 2018. After conversing with SC DHEC, I made the following assumptions when looking at agricultural permits within the study area. First, I removed all locations that were categorized as a building, since agricultural related runoff pollution cannot come from an enclosed area, since the animals are contained. The building itself is captured by the impervious surface data, which will be explained below. All locations that were only actively permitted outside of my study area date range, 2009 to 2017, were also eliminated. The three burial locations were eliminated for analysis, with the assumption that the permit holders were following good behavior and using proper burial techniques. The remaining 182 locations were narrowed to consider only those within the 34 delineated watersheds for this study, which left 38 total agricultural permits with the potential to affect *E. coli* levels within this my thesis analysis. Although these permit holders have clear expectations about how close they are allowed to spray irrigate or dry spread, I was informed that this does not always occur. SC DHEC has found farmers directly spraying into a water of the state according to the representative with whom I spoke (SC DHEC, personal communication, February 5, 2018). These permitted locations

lead to NPS pollution and point source pollution; however, they can be point source only if the permit holders are improperly applying the animal feces. They are more often NPSs due to precipitation and irrigation practices that lead to runoff that in turn ends up in local waters. I observed which watersheds had agricultural permits, which are noted below in **Table 5**.

For the NPDES locations, I first narrowed by location within the State of South Carolina to my study area. This left 85 permits. I then narrowed down by active permits with my study area date range, 2009 to 2017, which left 62 locations. Eleven of these were confirmed to be sanitary discharges by SC DHEC and were either domestic or municipal discharges. The remaining 51 locations required a Freedom of Information Act (FOIA) request to determine if their industrial discharge also contained sanitary sewer. After receiving this information, it was determined that 13 of these locations do discharge sanitary sewer, totaling 24 NPDES active permits for this study. I also noted which watersheds had NPDES permits (see **Table 5)**. These are point source pollutants and theoretically they should not exceed the standard, however, if proper effluent testing and elimination techniques are ignored, this could be a cause of additional *E. coli* in the system.

The NPDES permits appear to be more evenly distributed across these watersheds, with only the Saluda River watershed containing an abundant number of permits, at 17 total, while the agriculture permits were more clustered across the 34 watersheds, with only seven watershed containing these permits. The Saluda River watershed happed to have the most of these permits as well, with 18 total permits. Again

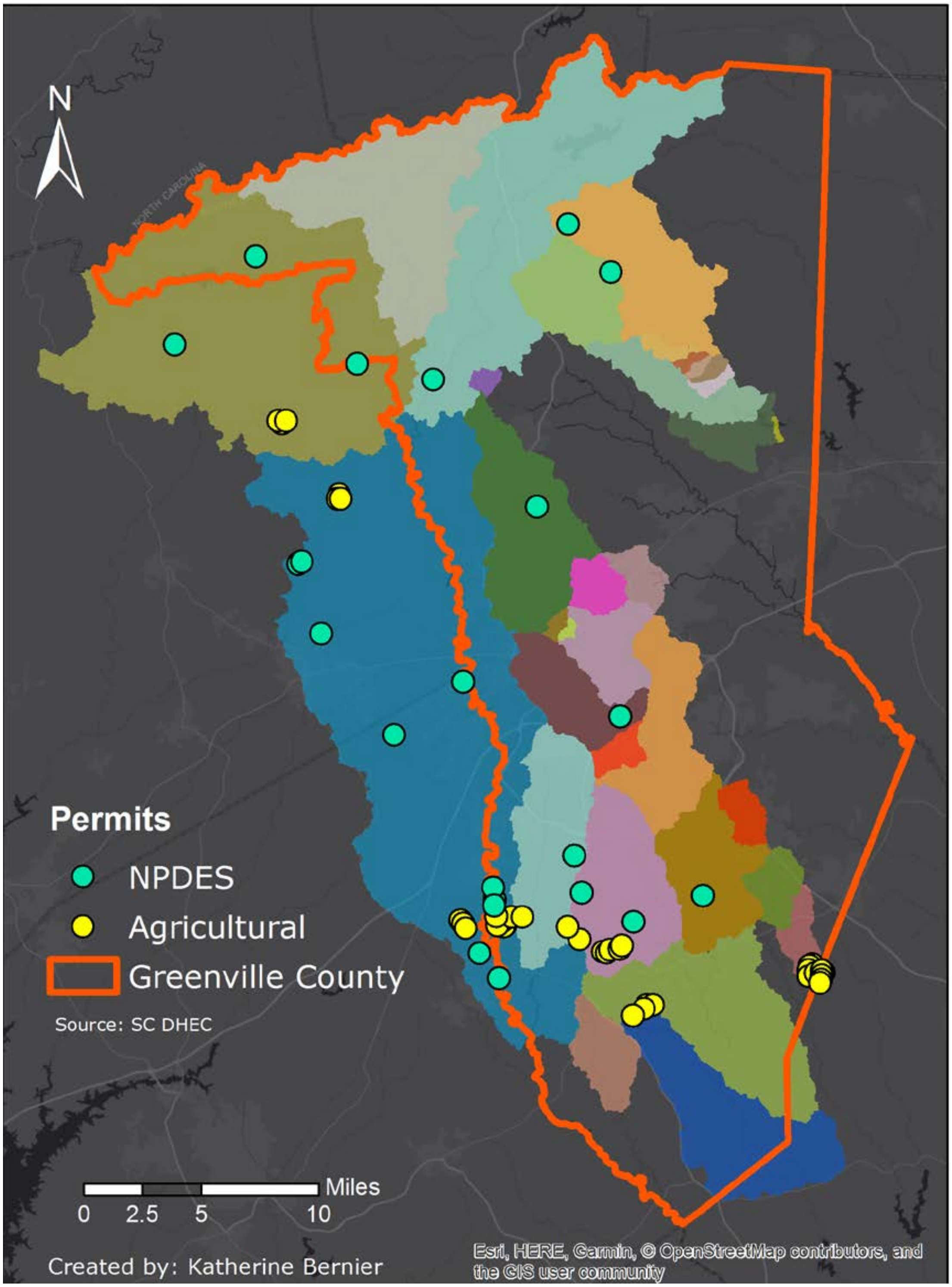
the limit for both of these permit types is a maximum monthly average *E. coli* level of 126 MPN per 100 ml or a daily maximum of 349 MPN per 100 ml (SC DHEC, 2017). Only abuse of these two permits would lead to elevated *E. coli* levels in adjacent waterways, suggesting that they should have a negative relationship, with *E. coli* sampling in any modeling analysis.

Table 5: Bacteria Related Permit Distribution by Thesis Study Watersheds

Site Name	NPDES Permits	Agricultural Permits
Bridge Road	2	0
Brushy Creek	0	0
Conestee	2	0
Cunningham Pt Ct	2	0
Fork Shoals	3	0
Grove Creek	1	3
Harbor Court	2	0
Hudson	1	0
Huff Creek	2	6
Hwy418	3	0
Hwy76	5	10
Jenkins Bridge Road	0	0
King Elder Way	2	0
Lake Cunningham	2	0
Lake Harbor Court	2	0
Lake Robinson	2	0
Landfill	2	0
Log Shoals	2	0
Middle Saluda	0	0
Mountain_ Creek	0	0
Mush Creek	1	0
North Saluda	1	0
Parkins	1	0
Payne Branch	0	10
Poole Road	2	0
Reedy River	5	7
Richland Creek	0	0
Rivers Street	1	0
Robinson Park	2	0
Rocky Creek	0	0
Saluda River	17	18
Salvation Army	1	0
South Saluda	4	3
Valley Road	0	0

Notes: Data available from SC DHEC

Figure 4: Permit Locations within Study Area Watersheds



Data Gathering Strategy: Land Cover & Land Use

In the attempt to correlated land cover and land use with *E. coli* I engaged two different sources of data. It is important to note that NLCD is based on land cover classes, which are broad categories that describe a general idea about land characteristics and are available at a 30-meter resolution for the entire United States and a 10 meter resolution for my study area. Land use is a more localized and a more detailed and descriptive categorization of land characteristics. I engaged land use by looking at impervious surface cover as a proxy, which will be discussed below. The addition of this data, although seemingly similar to developed land cover classes from the NLCD, is critical to include. Land uses are what planners control, through comprehensive plans and zoning. Hence, any correlation made between land uses as opposed to land cover with *E. coli*, as shown in the literature, which was the intent behind this thesis analysis, would be more informing to land use planning policy. Impervious surface data is commonly used as a proxy for land use within this body of research (DiDonato et al., 2009; Stumpf et al., 2010; Rowny and Stewart, 2012). I was not able to utilize more specific land uses due to the complex nature of the data and the availability of the specific land use transitions at the parcel level within all 34 watersheds.

The NLCD has the following available data for this analysis: 2001, 2006, and 2011. The 2016 data is scheduled to be publicly available in December of 2018, which is beyond my study timeframe. The land cover categories supplied by the NLCD were aggregated to 11 categories as shown below in **Table 6**. Land cover types, as defined by the NLCD, are widely accepted. Both land cover and land use classifications are difficult

in terms of directly relating them to the presence of animals on land, which may cause seasonal variation on bacteria loading. Also, land cover and land uses do not typically have clear transitions, though in Greenville County there is a distinctive difference between the headwater and the drainage as mention above.

Table 6: National Land Cover Database Categories: Aggregated for Thesis Study

Aggregated Land Cover	NCLD Categories
1. Open Water	Open Water
2. Developed, Open Space	Not aggregated
3. Developed, Low Intensity	Not aggregated
4. Developed, Medium Intensity	Not aggregated
5. Developed High Intensity	Not aggregated
6. Barren	Barren Land
7. Forest	• Deciduous • Evergreen • Mixed
8. Shrubland	Shrub/Scrub
9. Herbaceous	Grasslands
10. Agriculture	• Pasture/Hay • Cultivated Crops
11. Wetlands	• Woody Wetlands • Emergent Herbaceous Wetlands

I intentionally aggregated land cover subcategories by their parent category with the exception of the developed land cover categories. These were left separate to gain an understanding of the relationship between different levels of urbanization land cover and *E. coli*. To calculate the proportion of each of the 11 land covers within each sub-watershed, I utilized the Tabulate Area tool in the Spatial Analyst Zonal toolset. This data was then input into R statistical software to observe general trends as well as to predict the land coverage during the missing years for my study date range. I used simple linear regression to infer land cover proportions for 2009, 2010, 2012, 2013, 2014, 2015, 2016, and 2017 within each watershed. Scatter plots of the available data with the predicted

values revealed linear relationships within each watershed by land cover. The general slope trend per watershed are provided in **Table 7**.

Table 7: NLCD General Slope Trends	Open Water *	Developed Open Space ϒ	Developed Low Intensity ϒ	Developed Medium Intensity ϒ	Developed High Intensity ϒ	Barren *	Forest *	Shrubland ϒ	Herbaceous ϒ	Agriculture *	Wetlands *
Bridge Road	-	+	+	+	+	+	-	+	+	+	-
Brushy Creek	0	-	-	+	+	0	-	-	-	-	-
Conestee	-	-	-	+	+	-	-	+	+	-	-
Cunningham Pt Ct	-	+	+	+	+	+	-	+	+	-	-
Fork Shoals	-	+	+	+	+	-	-	+	+	-	-
Grove Creek	-	+	+	+	+	-	-	+	+	-	-
Harbor Court	-	+	+	+	+	+	-	+	+	-	-
Hudson	-	+	+	+	+	-	-	+	+	-	-
Huff Creek	-	+	+	+	+	-	-	+	+	-	-
Hwy418	-	+	+	+	+	-	-	+	+	-	-
Hwy76	-	+	+	+	+	-	-	+	+	-	-
Jenkins Bridge Road	-	+	+	+	+	-	-	+	-	-	-
King Elder Way	-	+	+	+	+	+	-	+	+	-	-
Lake Cunningham	-	+	+	+	+	+	-	+	+	-	-
Lake Harbor Court	-	+	+	+	+	+	-	+	+	-	-
Lake Robinson	-	+	+	+	+	+	-	+	+	-	-
Landfill	-	-	-	+	+	-	-	+	+	-	-
Log_Shoals	-	-	-	+	+	-	-	+	+	-	-
Middle Saluda	-	+	+	+	+	-	+	-	-	-	0
Mountain_ Creek	-	+	+	+	0	-	-	+	+	-	-
Mush Creek	-	+	+	+	+	-	-	+	+	-	-
North Saluda	+	+	+	+	+	+	-	+	+	-	0
Parkins	-	-	-	+	+	-	-	+	+	-	-
Payne Branch	-	+	+	+	+	+	-	-	-	-	-
Poole Road	-	+	+	+	+	+	-	+	+	-	-
Reedy River	-	+	+	+	+	-	-	+	+	-	-
Richland Creek	0	-	-	+	+	+	-	-	+	-	0
Rivers Street	-	+	+	+	+	-	-	+	+	-	-
Robinson Park	-	+	+	+	+	+	-	+	+	-	-
Rocky Creek	0	-	-	+	+	-	-	0	-	-	-
Saluda River	+	+	+	+	+	-	-	+	+	-	-
Salvation Army	-	+	+	+	+	-	-	+	+	-	-
South Saluda	+	+	+	+	+	-	-	+	+	-	-
Valley Road	0	-	+	+	+	0	-	+	+	-	0

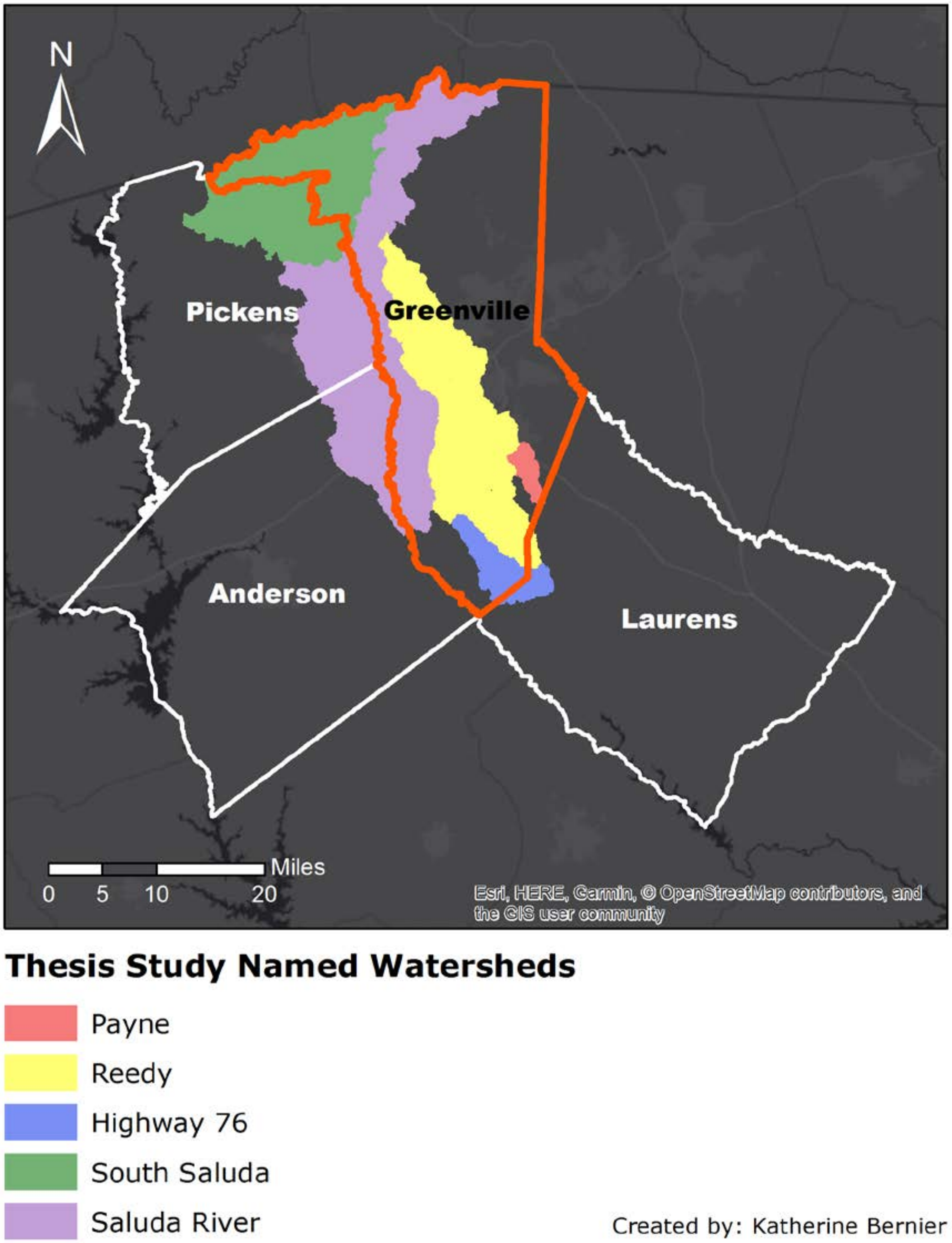
Note: Slopes are taken from the regression analysis performed in R to infer 2009, 2010, 2012, 2013, 2014, 2015, 2016, and 2017 land cover based on the known data Common Trends within each land cover category across the 34 watersheds are noted in blue (negative slopes)* and orange (positive slopes)ϒ

Due to the broad nature of land cover classifications, land uses based on impervious surface types from locally available annual data was engaged. Both Greenville County and the City of Greenville inventory impervious surfaces annually, which they then apply to their stormwater utility fees. Although their fee structures are different, they both charge property owners based on either land use or the amount of impervious surface on their parcels for the stormwater that they convey to the system. These funds are then utilized to provide services related to both water quality and quantity within the municipalities. The County has a single vector layer (ArcGIS) that is separated into 119 different impervious land uses. The City on the other hand has four separate vector layers (ArcGIS) including athletic courts, parking, sidewalks, and buildings. The buildings category is further separated into ten subcategories (all of these categories are provided in **Appendix A)**. The City data goes beyond the City boundary and in order to avoid double counting impervious surfaces these were all clipped to the boundary before merging them with the County data to create total impervious surface by year from 2009 to 2017. Total impervious area per watershed was then calculated by selecting and summing all impervious surface within the source layer feature, which was set to each watershed boundary individually. This impervious surface data does not include streets. The reason to eliminate roads from this discussion is that planners influence land use choice and they do not control roads. Since land use is the focus of this study, the impervious surface data that exists within each watershed that has the potential to change uses is of the most interest.

Five of the thirty-four watersheds within this study have borders outside of Greenville County (see **Figure 5**) and they cross into Laurens, Pickens, and Anderson County. This was not a concern for the land cover data availability, but it did affect the impervious surface data. Compared to the overall watershed, the Reedy, Highway 76 and Payne Watersheds are mostly contained within the county and the land area that does cross into Laurens County is primarily rural. At this time, Laurens County does not track impervious surface and for this analysis, these three watersheds considered only Greenville County imperviousness for the land use and *E. coli* analysis. The Saluda River watershed crosses into both Anderson and Pickens County. Anderson does not track impervious surfaces aside from streets, which were intentional omitted from this study. Pickens County, on the other hand, does track building impervious surface and I was able to obtain 2016 data to add to the impervious surface for the Saluda River watershed. I added this to every year assuming that since I was missing Anderson's data, I would not be highly biasing the earlier years in any way. The South Saluda watershed only overlaps into Pickens County and was treated in a similar fashion as the Saluda River watershed, by adding the 2016 Pickens data to all years. A visual depicting the total impervious surface available for analysis is provided in **Figure 6** (note that boundaries have been added to highlight these locations and hence the impervious surface is exaggerated). To further understand the developed land use category, I differentiated the total impervious surface data by the following specific land use types: parking, commercial/industrial, residential, multi residential, and other. I calculated the amount of each of these by year for each of the 34 watersheds. Although this enabled me to consider specific nuances

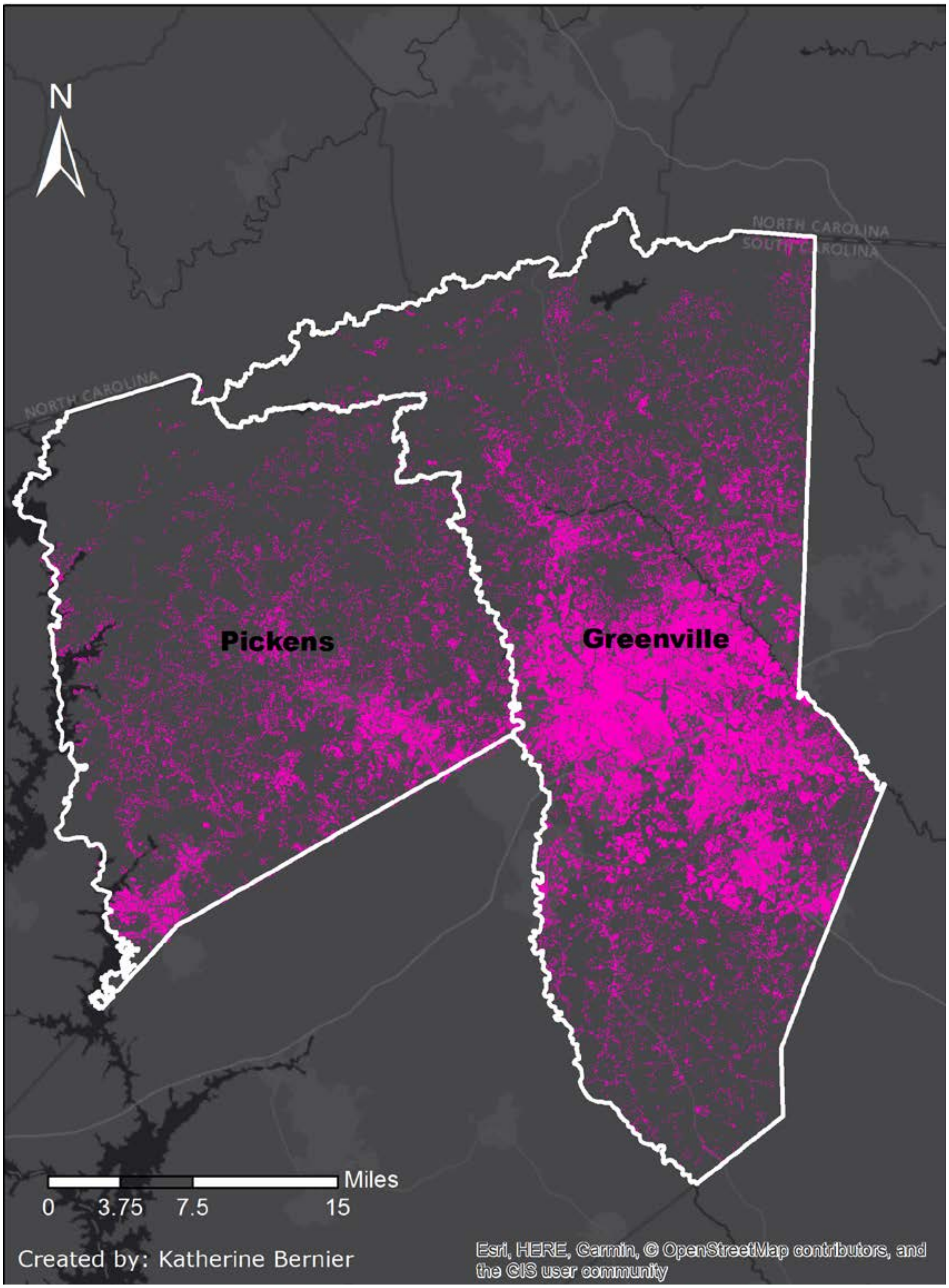
within these categories, they remain broad within this study. These categories assume similar land use choices within them, which is a major assumption for this study. There are certainly areas within the county that do not follow stereotypical land use patterns. For example, a commercial use could have pervious parking and an adjacent constructed wetland mitigating the pollutant loading from the high level of impervious surface. Another example would be a residential property could have minimal lawn surface and a high prevalence of domestic animal ownership, leading to spikes in *E.coli* pollution loading.

Figure 5: Study Area Watersheds Outside Greenville County Border



Created by: Katherine Bernier

Figure 6: Available Impervious Surface Data Coverage



Combining all of the above data from these three independent sampling strategies within Greenville County, this study sought to correlate land cover and land use with *E. coli* in the hopes of informing land use policy.

Statistical Analysis Method

The data for the statistical analysis discussed in detail above is summarized below in **Table 8.** These twenty predictors and response variables, based on these data, were input into R statistical programming software for multivariable regression analysis (R Development Core Team, 2010). Due to the nature of the sampling condition variable (x1), which is either wet, dry, or unknown, it was transformed into a dummy variable to analyze the different conditions separately: x1d1 ("unknown") and x1d2 ("wet"). This led to an increase to 21 total predictors, which means a total of 2,097,152 (2^{21}) possible models to calculate and filter for best model fit. All of these were computed for their potential for best describing *E. coli* levels in Greenville County Waters. Every *E. coli* measurement (response) was paired with a value for each predictor variable based on the year the grab sample was taken to match the current land cover, land use, and permitting at the time of the sample. As mentioned before, wet and dry conditions were determined for the City and County of Greenville by Woolpert, a consulting firm, and came with each individual *E. coli* sample. Both NPDES and agricultural permits were constant throughout the study timeframe, meaning they were all active at the time of sampling between 2009 and 2017. To determine the remaining predictors to pair with each *E. coli* value, a matrix was built in R, pulling the appropriate land cover and impervious data by land percentage annually based on the year of the *E. coli* sample. With all these variables,

land cover, land use, and two key permit types were engaged to understand their relationship to *E. coli*. I hypothesized that there was a relationship between land cover typology and impervious land uses with *E. coli* and I predicted that this study could lead to more informative policy adjustments. The null hypothesis was that no correlation could be determined between land cover or land use and *E. coli* levels in Greenville County. The results of this analysis, as well as a discussion of what was observed, are presented below in **Chapter 4**.

Table 8:
Regression Analysis Variables and Prevalence within the Study Area Watersheds

Regression Variables	Value	Range
Response Variable		
E. coli	MPN*	1-31,062
log(*E. coli*)	log transformed MPN	0-4.492
Predictor Variables		
x1 = Wet, Dry, or Unknown Conditions	"Wet", "Dry", "Unknown"	-
➢ x1d1 = "unknown" x1d2 = "wet"	Dummy Variables	-
x2 = Agricultural Permits	Number of Permits	0-18
x3 = NPDES permits	Number of Permits	0-17
x4 = Agricultural Land Cover	Percentage of Total Land Area	0.25% - 29.77%
x5 = Barren Land Cover	Percentage of Total Land Area	0% - 0.64%
x6 = Forested Land Cover	Percentage of Total Land Area	12.16% - 88.15%
x7 = Herbaceous Land Cover	Percentage of Total Land Area	0.40 - 13.67%
x8 = Highly Developed Land Cover	Percentage of Total Land Area	0% - 10.99%
x9 = Medium Developed Land Cover	Percentage of Total Land Area	0.05% - 20.25%
x10 = Low Developed Land Cover	Percentage of Total Land Area	0.37% - 30.57%
x11 = Open Space Developed Land Cover	Percentage of Total Land Area	5.16% - 35.05%
x12 = Open Water Land Cover	Percentage of Total Land Area	0% - 3.12%
x13 = Shrubland Land Cover	Percentage of Total Land Area	0% - 1.79%
x14 = Wetland Land Cover	Percentage of Total Land Area	0% - 4.47%
x15 = Impervious Surface	Percentage of Total Land Area	0.30% - 17.80%
x16 = Commercial Impervious Surface	Percentage of Total Land Area	0 .01% - 8.57%
x17 = Parking Impervious Surface	Percentage of Total Land Area	0% - 3.41%
x18 = Residential Impervious Surface	Percentage of Total Land Area	0.08% - 6.66%
x19 = Multi-Residential impervious Surface	Percentage of Total Land Area	0%-1.53%
x20 = Other Impervious Surface	Percentage of Total Land Area	0.08% - 2.04%

Notes: *MPN = Most Probable Number of *E. coli* per 100 mL

CHAPTER FOUR: RESULTS, IMPLICATIONS, & FINDINGS

Multivariable Linear Regression

In **Chapter 3** the variables for this analysis were introduced and the basic strategy for analysis was discussed. Before presenting the results, it is important to review some basic trends that I have observed. First and foremost, development in Greenville County is increasing overall, which has led to increases in impervious surfaces and decreases in forest, agriculture, wetlands, and open water land cover categories. As discussed in the literature review (**Chapter 2**), impervious surface increases often correlate to increases in pollutant loads within local waters. Also, due to the nature of these data, it was suspected that multicollinearity would be a concern with any statistical analyses, which will be explained below. The differences among my study area watersheds, which can be seen in **Table 8** by the ranges of land cover types, provided this study with a unique opportunity to correlate land cover categories and impervious surface as they relate to *E. coli* over the study timeframe (2009-2017). Again, I used impervious surface as a proxy for land use in order to increase the understanding of land choices and *E. coli* levels, beyond that which would be available by considering only NLCD classifications.

To begin, after an exploratory analysis with all predictor variables in R Software, I determined that a log transformation of the response variable (*E. coli* levels) would be needed to satisfy linear regression assumptions (R Development Core Team, 2010). The diagnostic results for the whole model from the log transformed *E. coli* values are available in **Appendix B**. These visuals appeared reasonable, with no obvious patterns that would suggest something other than a linear relationship between the predictors and

the log transformed response. Also, the normality plot did not reveal strong evidence that the residuals were not normal. Next, I ran best subset analyses to calculate all of the possible models and saved the results for observation and continued analysis. To sort through the over two million models computed by R and compare these possible regression models, I determined the best suggested models based on three model selection criteria: Akaike's Information Criterion (AIC), Bayesian Information Criterion (BIC), and Prediction Sum of Squares (PRESS) (equations provided below, **Figure 7**). These statistical methods "combine information about the [Sum of Squared Errors] SSE, number of parameters in the model, and the sample size" (Penn State 10.5, 2018, para. 1). Note that low values for these criteria indicate better model fit. BIC tends to favor smaller models due to the penalty the formula places on the number of parameters, which is the reason why in order to get a smaller BIC, more variables were removed from the model (Penn State 10.5, 2018). PRESS is calculated "by omitting each observation individually and then the remaining *n*-1 observations are used to estimate the regression function, which is used to predict the value of the omitted response" (Penn State 10.5, 2018, para. 5). The resulting value is then compared to the actual value by taking the difference to determine the accuracy of the estimated regression function. These statistical methods are a better way to measure model fit than the coefficient of determination, R^2, and R^2 adjusted, as R^2 will always increase when more variables are added to a model and both R^2 and R^2 adjusted do not make a statement about the strength of the relationship between the predictors and the response. Instead, they describe the reduction in the proportion of total variation in the equation being explained by the relationship between

the response and the predictors. For analysis and model building, it is important to note that x15, total impervious surface, is a linear combination of x16 through x20, which means that final models must consider either x15 or x16 through x20 but not both. Considering both would be giving double consideration to the same predictor. Also, the land cover categories, x4 through x14 add to 100 percent, representing the total land cover surface within Greenville County, which causes the intercept column to be written as a perfect linear combination of x4 through x14. This causes an identifiability problem given the infinite number of solutions that minimize the least squares objective function. For model building, I removed one of these variables.

Figure 7: Model Fit Criteria Equations

$$AIC_p = n\ln(SSE) - n\ln(n) + 2p$$

$$BIC_p = n\ln(SSE) - n\ln(n) + p\ln(n)$$

$$\text{PRESS} = \sum_{i=1}^{n}(y_i - \hat{y}_{i(i)})^2$$

Source: (Penn State 10.5, 2018)

To begin narrowing the number of models, I observed the top five to twenty models from each criterion. I processed each estimated regression function and examined the resulting coefficients, significance, potential for multicollinearity, model fit, and normality. Models that did not agree with the assumptions of multiple linear regression were set aside. Due to the multiple ways that imperviousness and developed land cover were being added to the model, I became quickly aware of the obvious multicollinearity concern within this regression model building. The top-rated models based on AIC, BIC, and PRESS criteria were all noted as having high multicollinearity issues. Even models

with fewer predictor variables were troublesome and I determined that a different approach to assessing the relationship and choosing a model would be beneficial.

I calculated Pearson's correlation for all the numeric terms and determined that the developed land cover categories were all strongly positively correlated with all of the various impervious land use observations as well as with each other (see **Table 9**). Those greater than 0.70 are considered highly correlated. Correlation is problematic because the predictors are attempting to explain the same relationship with *E. coli* based on the other predictors in the model. This forces some predictors to change sign in order to compensate for the competing variables. Based on the observed results, I noted three main strategies to consider to eliminate the multicollinearity. The first was to keep the NLCD developed categories as predictors (x8-x11), the second was to keep only total impervious surface as a predictor (x15), and the third was to keep the differentiated impervious surfaces as predictors (x16-x20). These three individual strategies alone were not sufficient to address the multicollinearity and some correlated terms remained within this model. For instance, it became apparent that the decrease in forested land cover was highly correlated to the increase in any of the developed categories, which indicated that one or the other needed to be used in the model. This introduced a fourth possible strategy, namely, to eliminate all developed land cover in potential models and observe models focused on forest cover, which I engaged as well. This strategy did not lead to any reasonable models. Changes in herbaceous and shrubland land cover (both increasing overall within these watersheds) strongly correlated with one another and herbaceous also strongly correlated with the decreasing agricultural land cover. Again, here was a second

set of variables within the land cover classification categories that were competing to describe the same trend with *E. coli*, due to their similar trends within my designated watersheds. For this reason, I eliminated x7, herbaceous land cover, from the analysis, satisfying the identifiability problem mentioned above. Finally, the number of NPDES permits and the number of agricultural permits, although completely unrelated in reality, were similarly distributed across the County, which was unexpected and led to another form of multicollinearity in the model. It was expected that they would produce a similar result within a model, but due to the similar trend across the 34 watersheds, separate observations could not be made. The permits were combined into one additive category to consider the presence and frequency of permits within each watershed.

Table 9: Pearson's Correlation Values for Numeric Predictors for *E. coli*

Variable	LogY	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20
LogY	1.00	-0.13	-0.19	-0.29	-0.41	-0.40	-0.40	0.41	0.44	0.45	0.44	-0.50	-0.38	0.21	0.43	0.41	0.31	0.44	0.43	0.36
x2	-0.13	1.00	0.90	0.39	0.31	0.25	0.27	-0.26	-0.29	-0.31	-0.34	0.05	0.41	0.04	-0.32	-0.28	-0.22	-0.38	-0.35	-0.19
x3	-0.19	0.90	1.00	0.20	0.29	0.26	0.21	-0.24	-0.26	-0.28	-0.29	0.10	0.32	-0.07	-0.29	-0.29	-0.11	-0.35	-0.33	-0.15
x4	-0.29	0.39	0.20	1.00	0.55	0.26	0.73	-0.43	-0.45	-0.53	-0.52	0.35	0.63	0.35	-0.53	-0.43	-0.40	-0.56	-0.61	-0.49
x5	-0.41	0.31	0.29	0.55	1.00	0.67	0.68	-0.76	-0.75	-0.78	-0.71	0.63	0.66	0.02	-0.79	-0.76	-0.55	-0.77	-0.78	-0.84
x6	-0.40	0.25	0.26	0.26	0.67	1.00	0.60	-0.92	-0.95	-0.95	-0.95	0.67	0.58	-0.49	-0.94	-0.91	-0.69	-0.91	-0.88	-0.84
x7	-0.40	0.27	0.21	0.73	0.68	0.60	1.00	-0.78	-0.77	-0.79	-0.70	0.49	0.88	0.17	-0.80	-0.79	-0.58	-0.77	-0.80	-0.67
x8	0.41	-0.26	-0.24	-0.43	-0.76	-0.92	-0.78	1.00	0.98	0.94	0.88	-0.67	-0.71	0.20	0.97	0.96	0.80	0.87	0.88	0.87
x9	0.44	-0.29	-0.26	-0.45	-0.75	-0.95	-0.77	0.98	1.00	0.96	0.93	-0.70	-0.71	0.27	0.97	0.96	0.75	0.91	0.91	0.85
x10	0.45	-0.31	-0.28	-0.53	-0.78	-0.95	-0.79	0.94	0.96	1.00	0.97	-0.69	-0.74	0.29	0.99	0.95	0.70	0.98	0.97	0.90
x11	0.44	-0.34	-0.29	-0.52	-0.71	-0.95	-0.70	0.88	0.93	0.97	1.00	-0.67	-0.68	0.38	0.95	0.88	0.69	0.97	0.94	0.86
x12	-0.50	0.05	0.10	0.35	0.63	0.67	0.49	-0.67	-0.70	-0.69	-0.67	1.00	0.37	-0.39	-0.68	-0.66	-0.51	-0.65	-0.66	-0.64
x13	-0.38	0.41	0.32	0.63	0.66	0.58	0.88	-0.71	-0.71	-0.74	-0.68	0.37	1.00	0.17	-0.74	-0.74	-0.50	-0.73	-0.75	-0.63
x14	0.21	0.04	-0.07	0.35	0.02	-0.49	0.17	0.20	0.27	0.29	0.38	-0.39	0.17	1.00	0.23	0.22	0.12	0.29	0.22	0.09
x15	0.43	-0.32	-0.29	-0.53	-0.79	-0.94	-0.80	0.97	0.97	0.99	0.95	-0.68	-0.74	0.23	1.00	0.95	0.77	0.96	0.95	0.92
x16	0.41	-0.28	-0.29	-0.43	-0.76	-0.91	-0.79	0.96	0.96	0.95	0.88	-0.66	-0.74	0.22	0.95	1.00	0.62	0.90	0.92	0.83
x17	0.31	-0.22	-0.11	-0.40	-0.55	-0.69	-0.58	0.80	0.75	0.70	0.69	-0.51	-0.50	0.12	0.77	0.62	1.00	0.64	0.59	0.70
x18	0.44	-0.38	-0.35	-0.56	-0.77	-0.91	-0.77	0.87	0.91	0.98	0.97	-0.65	-0.73	0.29	0.96	0.90	0.64	1.00	0.98	0.88
x19	0.43	-0.35	-0.33	-0.61	-0.78	-0.88	-0.80	0.88	0.91	0.97	0.94	-0.66	-0.75	0.22	0.95	0.92	0.59	0.98	1.00	0.87
x20	0.36	-0.19	-0.15	-0.49	-0.84	-0.84	-0.67	0.87	0.85	0.90	0.86	-0.64	-0.63	0.09	0.92	0.83	0.70	0.88	0.87	1.00

Note: These values were calculated in Excel and the gray highlighting is for ease in viewing the data and the deep orange highlighting is to draw attention to all highly correlated (both positive and negative) variables (≥|0.70|). The key for the variables is included in **Table 8.**

Even though these 34 watersheds are very different from a land cover standpoint in some cases, the overall land cover trends were similar. This similarity created a challenge for building a model that was both defensible and logical. After working through removing the strongly correlated predictor variables based on the three development-focused strategies mentioned above, potential models were narrowed down to a handful of possible options that no longer demonstrated multicollinearity. The process of removing variables is subjective, although it follows a logical and scientific process (Penn State 12.4, 2018). For this study, I was most interested in the effects of development and I retained at least one form of land cover or land use that described development in each model.

The linear regression modeling process revealed some expected results as well as some surprising ones upon first observation. It appeared that in all possible models (including those that had multicollinearity), the "wet" designation was highly significant and had a strong positive relationship to *E. coli* levels. Other variables, such as agricultural land cover, which was expected to display a positive relationship to *E. coli* based on the literature discussion in **Chapter 2**, instead were inversely related to *E. coli* based on the presence of other variables in the model, likely attributed to the multicollinearity. Observing these results over and over led to the following potential explanation. It is possible that knowing the sampling condition (wet versus dry) is not only critical to determining a final linear regression model for the relationship between land cover and/or land use and *E. coli*, but that it also dictates the model and diminishes other predictor variables. Wet conditions appear to be the main cause of elevated *E. coli*

levels, which is not surprising since wet conditions can be used to explain many of the sources for *E. coli*. If the presence of the bacteria is due to NPS, then storm events are expected to elevate *E. coli* within a local waterbody and the more developed or *E. coli* producing land cover and land use types that are within the watershed tend to exacerbate the problem due to increases in runoff. As noted in **Chapter 2**, in the literature, *E. coli* does not appear to demonstrate first flush behavior, and spikes are noted sometimes at the end of a storm event. It hence seems logical that *E. coli* samples taken during the storm event, at nearly any point, could be elevated. It is unclear, however, if the increases in bacteria are due to runoff from the storm event itself or the potential stirring up of bottom sediment, where it has been found that *E. coli* can colonize and survive, as discussed in the literature review (**Chapter 2**).

Other Regression Methods

Before I committed to a linear regression model, I briefly considered time series regression. Lack of data prohibited time series from being a reliable model choice, since the date range for each sampling location was not consistent. It was also evident that the lack of a sampling condition differentiation for the SC DHEC data rendered a time series regression impractical, since knowledge of wet weather conditions could drastically change the interpretation. I would have required more data to consider only those sampling locations provided by the County and the City of Greenville to attempt an understanding of any trends shown in a time series regression model. I also considered and attempted a penalized regression technique called an elastic net estimator to estimate the model, which is a combination of LASSO and ridge regression, commonly used when

multicollinearity is present between predictor variables. (Lee, Nguyen, & Wang, 2016). I found this method to be insufficient for this study.

Regression Findings

The reduced model results, shown in **Table 10**, were the most defensible among those analyzed and they no longer displayed multicollinearity. All three models include the wet sampling condition, the combined permit variable, and a variable or variables describing developed land use or land cover. The first model (**Model 1**) considers a combination of residential impervious surface (x18+x19), the second (**Model 2**), total impervious (x15), and the third (**Model 3**) a combination of all developed land cover variables (x8+x9+x10+x11). Shown below is the summary of the model results, p-value, F-statistic, coefficient of determination, and the VIF, or Variation Inflation Factor, which is a test for multicollinearity. Although there is not a specific value that determines if multicollinearity is an issue within model building, values as small as four can indicate a potential concern in terms of model building (Penn State 12.4, 2018). These models passed basic diagnostics and no longer contained multicollinearity, though it should be noted that normality plots were barely defensible. In these severely reduced models and based on the presence of the remaining variables within each of these models, the combined permits predictor was less significant in describing the relationship with *E. coli* than the wet sampling condition and the developed land cover or land use. The combined permits were significant between 90% and 95% confidence levels, while the other variables were significant at all standard confidence levels and are reported below. The R Software results are reported in **Appendix C**.

Table 10: Reduced Linear Regression Model Results

Model 1					
Variable	Estimated Coefficients	Standard Error	t value	p value	VIF
Intercept	4.5761	0.0934	48.983	<2e-16	
"wet"	2.175	0.0998	21.792	<2e-16	1.170
x2+x3	-0.0103	0.0603	-1.712	0.0872	1.166
x18+x19	0.1954	0.0211	9.259	<2e-16	1.349
R^2	0.4167		Adjusted R^2	0.4153	
F-statistic	294.8		p-value	<2.2e-16	
Model 2					
Variable	Estimated Coefficients	Standard Error	t value	p value	VIF
Intercept	4.6599	0.0910	51.229	<2e-16	
"wet"	2.1875	0.1009	21.671	<2e-16	1.184
x2+x3	-0.0152	0.0059	-2.568	0.0103	1.115
x15	0.0752	0.0088	8.512	<2e-16	1.310
R^2	0.4108		Adjusted R^2	0.4093	
F-statistic	287.7		p-value	<2.2e-16	
Model 3					
Variable	Estimated Coefficients	Standard Error	t value	p value	VIF
Intercept	4.4542	0.1062	41.923	<2e-16	
"wet"	2.1560	0.1012	21.304	<2e-16	1.198
x2+x3	-0.0148	0.0059	-2.506	0.0123	1.110
x8+x9+x10+x11	0.0174	0.0019	8.999	<2e-16	1.319
R^2	0.4146		Adjusted R^2	0.4131	
F-statistic	292.2		p-value	<2.2e-16	

From the three models that emerged, it is apparent that the “wet” sampling condition is highly indicative of elevated *E. coli* levels. Second, regardless of which type of development I modeled (combined residential, total impervious, or combined developed land cover), all of them revealed a positive relationship with *E. coli.* Finally, the combined permits revealed an inverse relationship with *E. coli,* which could indicate

that the presence of permitting for uses that have the potential to cause elevated bacterial pollutant loadings are mitigating those sources, which is their intention. Revealing that the permitting process helps to mitigate *E. coli* pollution is an optimistic observation, especially considering the biased outlook about bad behavior witnessed with agricultural permits in South Carolina by DHEC representatives, as discussed in **Chapter 3**. Although these models are fairly reasonable and explain roughly 40 percent of the variance in the model, they do not engage the combination of land cover and land use that was hypothesized to be related to *E. coli* levels, given the reduction in predictor variables. For this reason, I performed Factor Analysis (FA) for these data, which also addressed the extensive multicollinearity concern.

Factor Analysis

Factor Analysis provides a "quantitative assessment of the strength of a series of factors", often referred to as components, in explaining the variance of predictors in a data set (Wayland et al., 2003, pg. 184). FA is a common statistical analysis for land use studies and has been extensively implemented in the literature to identify land use effects on surface water chemistry (Riitters et al., 1995). It is also a statistical method that is used when correlated variables are observed within a data set (Riitters et al., 1995). FA does not require normalized data, but skewed data can be problematic, and hence, I left the response variable, *E. coli*, log transformed, which is also common in FA (Wayland et al., 2003). FA allowed my study variables to compound with one another, permitting interactions between the predictors to take place and provided an understanding of the

relationship that groups of predictors has on *E. coli*. The chosen predictor variables for this thesis study proved to be the perfect candidate for FA.

Factor Analysis Findings

To determine the number of components, Eigenvalues are calculated based on values presented in a correlation matrix, similar to the Pearson's correlation matrix in **Table 9** (Wayland et al., 2003). Essentially, the predictors that are most correlated get pushed onto a single component based on their correlation. The components, formed by the grouping, are new predictors, which could be referred to as meta variables. I chose the most common method for choosing the number of components, which is narrowing to only the components that had an Eigenvalue greater than one (Riitters et al., 1995 and Wayland et al., 2003). The strength that each individual variable loads onto a component is based on the relationship each variable has to the other variables. I noted the following observations from the results of the FA.

Based on Eigenvalues, there were three resulting components that the predictors were loaded onto; component one had an Eigenvalue of 11.449, component two, 2.061, and component three, 1.506 (the complete output is provided in **Appendix C**). These three components explain 83.42% of the variance in the model as determined by FA. Rotations of the components in space can improve interpretation and I chose a quartimax rotation (**Table 11**), which places as much of the variance as possible onto the first component; the first component had a substantial amount of the loading and alone explained 63.60% of the model variance. The component matrix, **Table 11**, shows that these three components can be categorized as the following: component one compiled all

the developed land covers and land uses and sampling condition; component two focused primarily on the permits; and component three described a separate source for *E. coli* that included agriculture and wetland land cover. The third component is not as definitive as the first two, but it appears to be another category related to *E. coli* levels. The individual matrix values represent the loadings of each predictor onto the component. The closer the number is to the absolute value of one, the stronger the correlation between the variable and the component, and hence the stronger the loading. For example, x2 and x3 have values of 0.925 and 0.942 respectively, indicating a very strong loading onto component two. Values between +/- 0.4 and 0.5 are considered to be moderate loadings (Wayland et al., 2003).

Table 11: Quartimax Rotation Component Matrix for Factor Analysis

Rotated Component Matrix			
	Component		
Variable	1	2	3
x1	0.589	0.052	0.314
x2	-0.269	0.925	0.134
x3	-0.233	0.942	-0.032
x4	-0.532	0.143	0.642
x5	-0.811	0.072	0.268
x6	-0.938	0.045	-0.283
x8	0.959	-0.001	-0.009
x9	0.972	-0.035	0.043
x10	0.989	-0.065	0.014
x11	0.959	-0.102	0.097
x12	-0.743	-0.147	-0.186
x13	-0.726	0.204	0.451
x14	0.266	-0.020	0.907
x16	0.939	-0.067	-0.018
x17	0.760	0.079	-0.009
x18	0.959	-0.149	0.000
x19	0.95	-0.131	-0.077
x20	0.917	0.083	-0.131

Note: Principal Component Analysis was the chosen extraction method.
A quartimax rotation with Kaiser Normalization was utilized.

The three components were then used for multiple linear regression analysis in place of the original predictors to determine their significance on the log transformed *E. coli* response (full output provided in **Appendix C**). It was determined that component one was highly significant, component two was significant to the 95% confidence level, and component three was insignificant. As expected, component one had a positive coefficient (0.393) indicating that increases in developed land cover and land use (and decreases in forest, barren, and shrubland land cover) likely lead to elevated levels of *E. coli*. I speculate that missing sampling conditions for the SC DHEC data had an effect on

the degree to which x1 loaded onto component one, although it clearly correlates to the developed land cover and land use predictors. Component two revealed that increases in the number of permits decrease *E. coli* levels (-0.44), which indicates that permits appear to be performing as intended. Without the restrictions on effluent discharge (NPDES) and fecal matter land spreading (agricultural permits), these two sources of *E. coli* could have a positive effect on levels rather than the inverse effect that is observed, although this statement is a speculative, it is the product of a logical assertion. Finally, the low adjusted R^2 value from this regression model (0.211) suggested that one or more variables were missing, which could include other sources of *E. coli* that I did not include in my analysis (see *Limitations of Analysis* below and **Chapter 5**). Between the linear regression analysis and FA, my study confirmed some of the challenges and pitfalls to utilizing *E. coli* as an indicator for fecal pollution. Also, the results of this work indicate the need for future analysis, which will be discussed below in **Chapter 5**.

Limitations of Analysis

There are several limitations that must be addressed in this work, some of which were described in earlier sections; others are enumerated here. First, it is important to note that I relied on primary data, collected by SC DHEC, and the City and County or their contractors, each of whom had different objectives, sampling methodology, and data availability. With the disparate sampling processes and lack of similar data across the three data sets, I did not include other parameters, such as turbidity, which could have affected model fit. Some of the limitations relate to my original hypothesis, which was to focus primarily on land cover and land use. The NLCD, although widely available, is not

localized and detailed, and using it for local land cover observations is not as specific as ascertaining actual land uses by parcel. This disaggregation was not possible within the study time constraints, but should be addressed in future work. Other studies have proposed considering population density or specific agricultural crop practices (Wayland et al., 2003). Also, specific livestock prevalence and sewer coverage are additional data that could further differentiate land uses within Greenville County (Vitro et al. 2017). The other impervious surface land use category I engaged could also be further differentiated to better understand those land uses. Finally, within more specific land use explorations, it could be beneficial to consider actual buffer networks around each study area waterbody as well as existing BMP prevalence (both natural and proprietary) to discern the effects these have on bacterial water quality. Utilizing any of the above, could also increase the R^2 value within the statistical analyses. All of these proposed analyses, with more detailed parcel by parcel observations would be easier to accomplish with fewer watersheds.

Additionally, the intent of this study meant disregarding other potential sources of *E. coli*. I did not gather data associated with two types of human waste concerns, SSO data and septic tank data, for the following reasons. Within the City of Greenville alone, thousands of gallons of unpermitted SSO discharges occur annually and there are others that occur outside of the City boundaries (City of Greenville, personal communication, February 23, 2018). Although the City tracks this information, retrieving commensurate County data would have been far more complicated, since not all amounts of SSOs must be reported legally from each individual sewer company whom records these discharges.

In general, SSOs were not included because of the additional analysis complications associated with understanding the hydrologic nature of each waterbody, the rate at which the SSO moved throughout the water network, and a dilution factor based on water volume. Septic tanks are dichotomous, as there are only a handful within city limits but many exist within Greenville County. Compromised septic tanks can lead to bacterial pollution and recently, two watershed areas adjacent to the Reedy River received Section 319 grant money to address septic failures, which is a known concern in this area (RRWQG, 2016). Without being able to easily quantify septic tank prevalence and condition, I omitted them from my study, but acknowledge their potential impact (RRWQG, 2016). However, including these variables could potentially increase the R^2 value. Additionally, this analysis did not directly focus on specific GSI and LID BMPs, which remains a large gap in the literature, as well as provides a topic for future research. These remaining literature gaps should spark future work and will be discussed in **Chapter 5**.

Finally, as with anything that involved a single researcher, human error is a concern. Whenever possible, numeric observations were entered into Excel with calculations to check for accurate data transferal from ArcGIS. For example, every watershed had 100% of land cover accounted for based on total land cover from the NLCD, which was calculated from the sum of all land cover types. In this way obvious mistakes were caught and fixed immediately. Also, I maintained and performed a certain level of quality control and quality assurance to verify that measured or calculated values made logical sense. Even with these precautions, human error could still be a concern.

Policy Implications

I hypothesized that there was a relationship between land cover typology and impervious land uses and *E. coli* and I predicted that my study could lead to more informative policy adjustments. The null hypothesis was that no correlation could be determined between land cover or land use and *E. coli* levels in Greenville County. Although my model results were not strong, they all revealed a direct positive correlation between *E. coli* and developed land cover and land uses in Greenville County, which is consistent with literature. The inverse relationship between permitting (NPDES and agricultural) and *E. coli* was significant and valuable to observe, as this is the intent behind these permit restrictions and it indicates that policy implementation can provide desirable results. Finally, there are very few proprietary BMP solutions that have been proven to decrease bacteria loadings at a significant level, as discussed in the literature review (**Chapter 2**). More research is needed in order to provide thoughtful recommendations; however, the utilization of proprietary BMP solutions, such as inlet filters, within local ordinances should be used sparingly, especially as they relate to bacterial pollution mitigation. Additionally, it is common knowledge that without proper maintenance of BMPs including inlet filters and similar devices, they fail. Careful consideration of how to implement inspections of these BMPs is also necessary as it relates to policy.

Planners need to be aware of water quality sampling practices and results within their jurisdiction. It is critical for planners to be informed as cities continue to increase their urban densities, since it is a planners' role to provide land use recommendations and

it is known that these decisions can have a direct effect on local water quality. As shown in this research, developed land cover and land uses can affect bacteria water quality levels and requiring permits for related land uses can produce desirable results. Planners should be involved in water quality discussions; they should confer with local engineers about policies related to their zoning ordinances and comprehensive plans that can relate to MS4 permitting and other water quality restrictions produced outside of their direct responsibilities. Land use planning and water quality are deeply correlated; in Greenville County, as development and population growth continue to increase, mitigating the negative effects of this relationship should be immediately considered.

CHAPTER FIVE: CONCLUSIONS AND FUTURE WORK

Conclusions

Water quality monitoring analysis is both time consuming and complicated. Some of the most successful water quality monitoring projects have taken years of thorough data collection with thoughtful sampling strategies, such as the Chattahoochee project discussed above in **Chapter 2** (Lawrence, 2012). My thesis project set out to analyze existing data to determine if all the hours of preformed sampling could illuminate a potentially important relationship between land use choices and related polices and *E. coli* contributions during a pivotal moment in one of the fastest growing areas of the United States.

First, it is clear that there are different strategies and frequencies in water quality monitoring, not only within Greenville County, but also across the United States. Even though local concerns should dictate specific areas of focus for pollution mitigation, it is widely known that bacteria are a widespread problem. Pathogenic pollution in our waters is caused by both point sources and NPSs from failing infrastructure, SSOs, CSOs, and animal fecal matter. Second, the way in which we analyze and interpret water quality lacks consistency, accountability, and general understanding. Pathogen indicators such as *E. coli* are no exception, and in fact, *E. coli* as an indicator is one of the more confusing, complicated, and misunderstood pollutants. *E. coli* has diffuse origins that complicate the understanding about its control, as well as the dangers associated with the pathogens of which it is an indicator. It is known that the origins of pathogens in our local waters vary based on animal prevalence (wildlife, livestock, and pet), type and age of sewer

infrastructure, occurrence in bottom sediment, recent storm events, and the hydrology of a watershed. Hence, the human health and environmental concerns are not implicit since the strains of *E. coli* that are present in these varied sources may cause different levels of harm.

Most importantly, understanding the implications of growth and development on the environment and applying that knowledge to thoughtful planning to better protect our both human and ecological health should be considered in the early stages of growth, not later. This is especially timely to consider in Greenville County, as both the northern and southern sections of the County, outside of the most developed center, are unzoned. The pressure to develop these areas are simply a matter of when and not if, as land demands will push into these rural areas. For these reasons, future research is needed for *E. coli* as well as other FIB, which may provide a less convoluted understanding of localized fecal bacteria concerns.

Future Work

My work was the tipping point of a much larger project, and there are many areas of future work that can evolve from this thesis. First, it is evident that a thorough study of wet versus dry sampling conditions during grab samples for *E. coli* needs to be studied. Filling this knowledge gap in the literature would provide the environmental community, including planners, engineers, governmental agencies, and NGOs, helpful information to make more informed and educated recommendations for land use planning that improves rather than degrades water quality. It would also be useful to further analyze these data. Potentially adding more locations beyond Greenville County could provide better

watershed differentiation, although I am skeptical that this strategy would have similar results. On the other hand, it is possible that analyzing only similar land cover or land use watersheds could provide a clearer statistical relationship. To accomplish this, I would group watersheds by similar land cover classifications or land uses and analyze the regression models produced for each type separately. For example, majority forest, highly urbanized, and agriculture heavy watersheds could be grouped and could lead to different coefficient results and more specific conclusions. For an analysis that engaged this approach, more locations would be needed than those engaged in this study, especially since grouping these watersheds by land use prevalence would decrease the number of observations for each regression model. Another option would be to gather more specific land use data, proposed above, that goes beyond just using impervious surface as a proxy for all land use and then rerunning the statistical analysis design from this thesis.

Additional analyses would involve retrieving more water quality data in the future by continuing water quality monitoring at some of these locations. One easy and affordable addition to any grab sampling process would be to require a turbidity measurement at the time of grab sample collection to better understand the relationship between *E. coli* and turbidity. Although I do not believe this is helpful for land use policy recommendations, it has been shown to be a helpful informant of human recreational use. Other *E. coli* sampling that should be performed is an in-depth wet versus dry weather analysis, with strategic watersheds chosen that have different land use makeups. Also, with any new sampling methodology, I would suggest the addition of different FIBs to aid in understanding the source of the bacteria, which is an important recommendation

based on the thesis' primary research objective. Without a thorough understanding of the land and water quality nexus, which *E. coli* alone cannot provide, land use choices—including BMP decisions and policies—will continue to be ill-informed, leading to poor funding allocation decisions and irresponsible pollution mitigation strategies.

APPENDICES

APPENDIX A: LAND USE CLASSIFICATION DEFINITIONS

Greenville County*	
0110	Duplex
0112	Multiplex
0113	Group House Converted
0120	Apartment – Conventional (C,D)
0120	Apartment – High Rise (A,B)
0122	Apartment Subsidized
0130	Mobile Home Park
0140	Nursing Home
0141	Assisted Living
0142	Healthcare – Converted Residential
0143	Healthcare – High – Rise Retirement with Dining
0230	Apartment – Boarding/ Bed & Breakfast
0240	Hotel – Luxury
0240	Hotel – Full Service Upscale
0250	Motel – Extended Stay
0270	Motel – Mid – Service
0271	Motel Economy
0272	Motel Budget
0273	Motel Low Cost
0300	Car Wash Full Service
0301	Car Wash Self Service
0301	Car Wash Automatic
0310	Service Station – Gas
0320	Cashier Booth – Gas
0330	Service Garage – Body Shop
0331	Mini Lube
0332	Auto Service Center
0350	Auto Dealership/ Maintenance/ Service
0360	Auto Dealership/ Showroom
0370	Parking Garage
0370	Parking – Basement Level
0371	Parking Lot
0409	Medical Office – Dental
0410	Medical Office
0411	Vet Clinic
0413	Rehab Center
0414	Vet Clinic Converted / Residential
0420	Office High Rise
0421	Office – General
0423	Office – Converted/Residential
0424	Office/Warehouse
0425	Office Retail Strip
0430	Bank Full – Service
0431	Bank Branch
0510	Convenience Store
0511	Convenience Store/Food Service
0512	Mom/Pop Grocery
0513	Super Market
0520	Retail – General
0521	Retail – Strip Center
0522	Retail – Show Room
0523	Retail – Drug Store
0530	Retail – Discount
0531	Retail – Discount Warehouse
0532	Retail – Lumber – Showroom/Retail
0550	Shopping Center/ Neighborhood
0560	Shopping Center/Mall
0561	Shopping Center Anchor Retail
0570	Shopping Center Department Store
0580	Barber/Beauty – Converted Residence
0581	Barber/Beauty – Conventional
0590	Laundry/Cleaner Full Service
0591	Laundry Mat – Self service
0610	Restaurant – Fast Food
0611	Restaurant – Truck Stop
0620	Restaurant – Full Service
0620	Cafeteria
0630	Bar – Neighborhood
0631	Bar – Night Club
0632	Bar – Restaurant/Lounge/ Sports

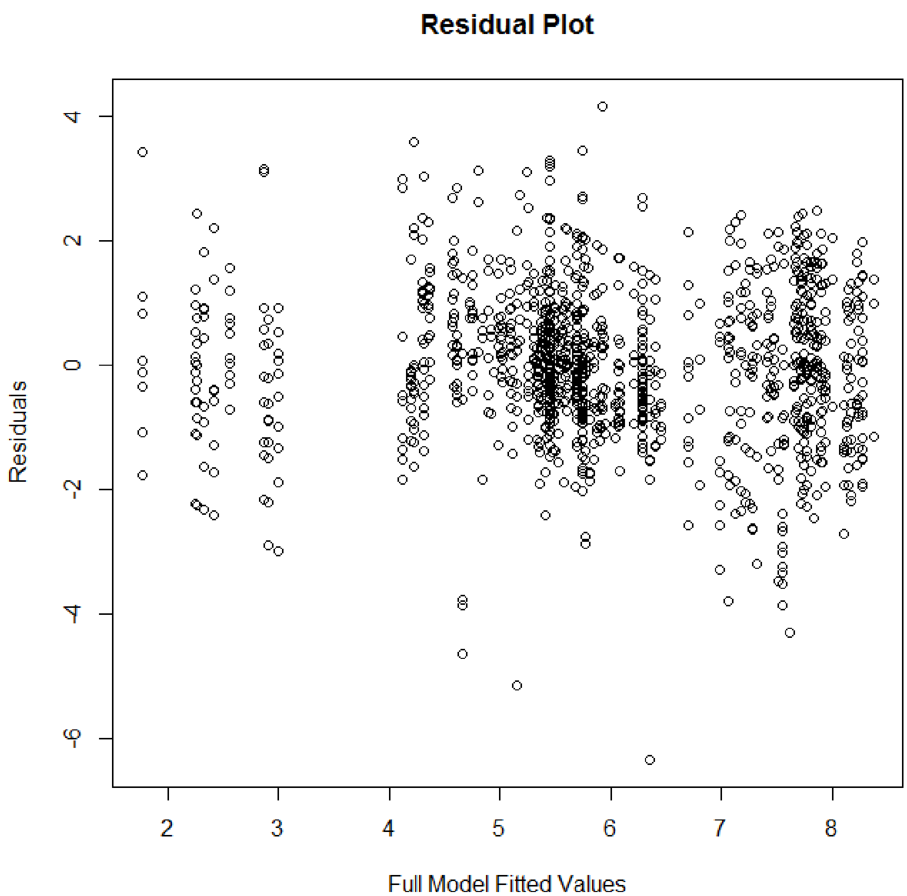
0710	Recreation – Bowling Alley
0720	Recreation – Gym/Athletic Club
0721	Recreation – Health Club
0730	Recreation – Skating Rink Ice
0730	Recreation – Skating Rink Roller
0740	Movie Theatre
0741	Theatre – Play/Dining
0750	Recreation – Golf – A
0750	Recreation – Golf – B
0750	Recreation – Golf – C
0750	Recreation – Golf – D
0751	Recreation – Club House/Golf
0752	Recreation – Golf – Putt Putt
0753	Recreation – Recreation – Golf – Par 3
0754	Recreation – Country Club
0755	Recreation – Horse Arena
0770	Recreation – Community Recreation
0780	Recreation – Theme Park
0790	Recreation – Tennis/Racquet
0805	Cemetery
0810	Religious/Church
0821	Government
0850	Schools
0851	Day Care – Conventional
0852	Day Care – Converted Residential
0860	Fraternal Organization
0872	Funeral Home Conventional
0873	Funeral Home Converted
0890	Broadcasting Facility
0891	Utility
0910	Mini-Warehouse
0920	Golf Storage/Service

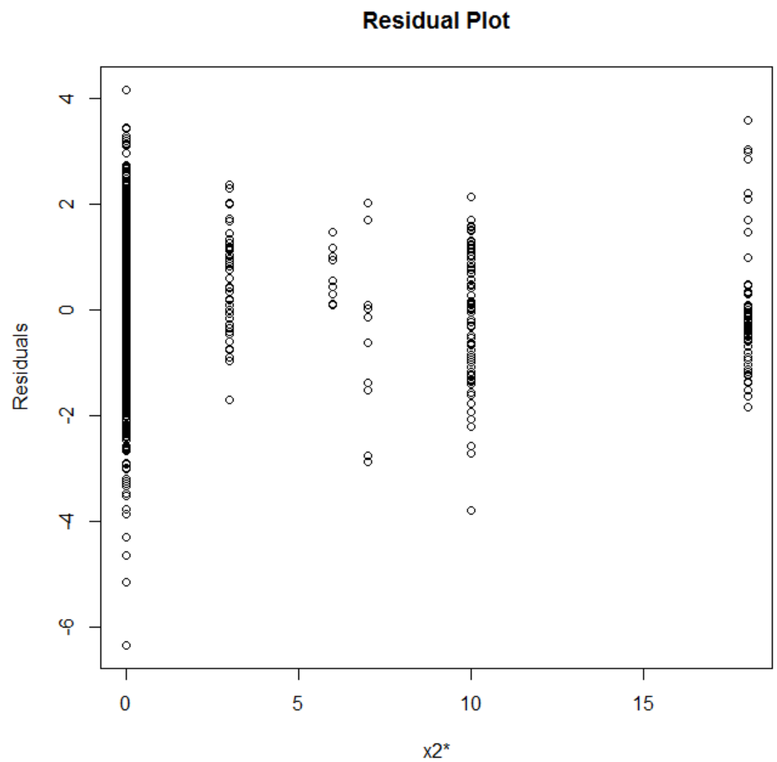
0930	Truck Terminal
0940	Warehouse General
0950	Warehouse Distribution
0960	Warehouse – Multi – Purpose
0970	Industrial
0980	Hangers
0990	Cold Storage
1100	Residential Single Family
1101	Residential Single Family – with Auxiliary Use
1170	Residential Mobile Home with Land
1171	Residential Mobile Home on Mobile Home File
1180	Residential Vacant
1181	Homeowners Association Property
1182	Common Areas
6800	Commercial Vacant
9170	Agricultural Vacant
9171	Agricultural Improved
City of Greenville**	
Buildings	
20	Commercial/Industrial
21	Residential – Multi
23	Residential
23	Mixed Use
24	School
25	Parking Structure
26	Accessory Structure
27	Under Construction
29	Other
30	Group Quarters
Athletic Courts	
Parking	
Sidewalks	

__Notes:__ *Information retrieved from http://www.gcgis.org/website/Docs/landuse.pdf
**Data provided by the City of Greenville

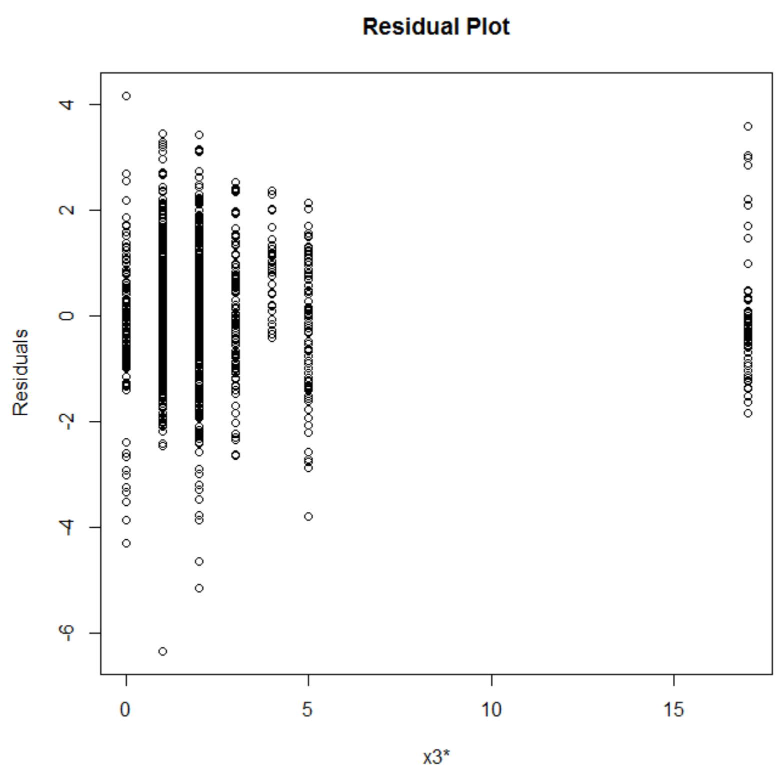
APPENDIX B: REGRESSION MODEL OUTPUT RESULTS

Included here are the diagnostic results for the model with all predictor variables for the purpose of providing visual diagnostics only. First is the fitted values plotted against the residuals, second are each numeric predictor variable plotted against the residuals and third, is the normality plot.

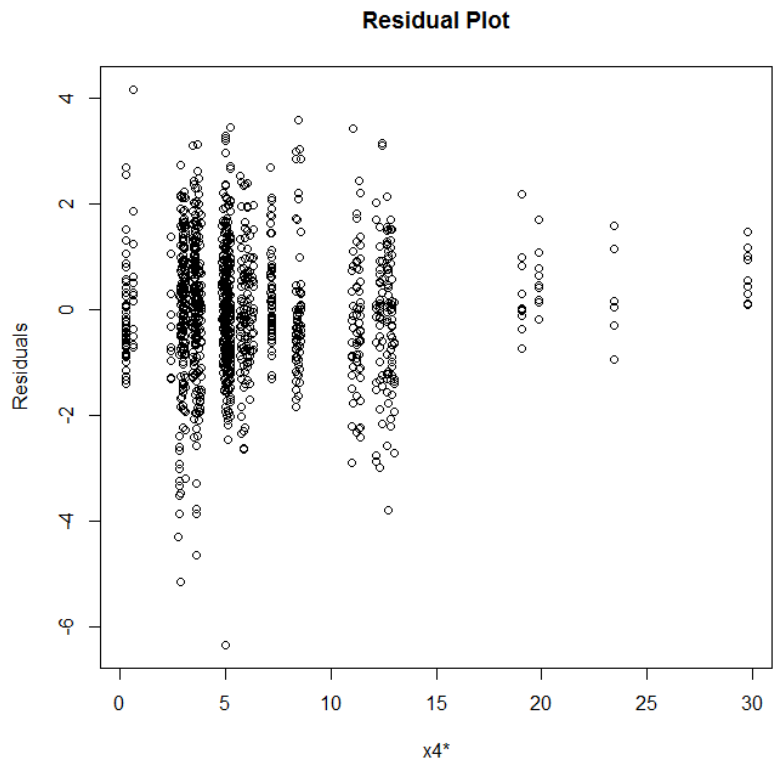


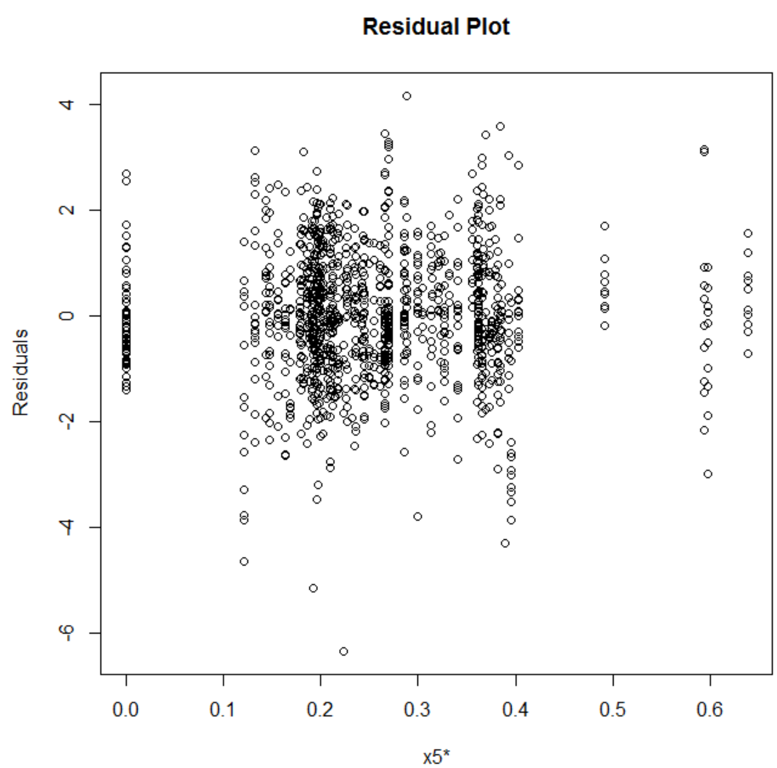


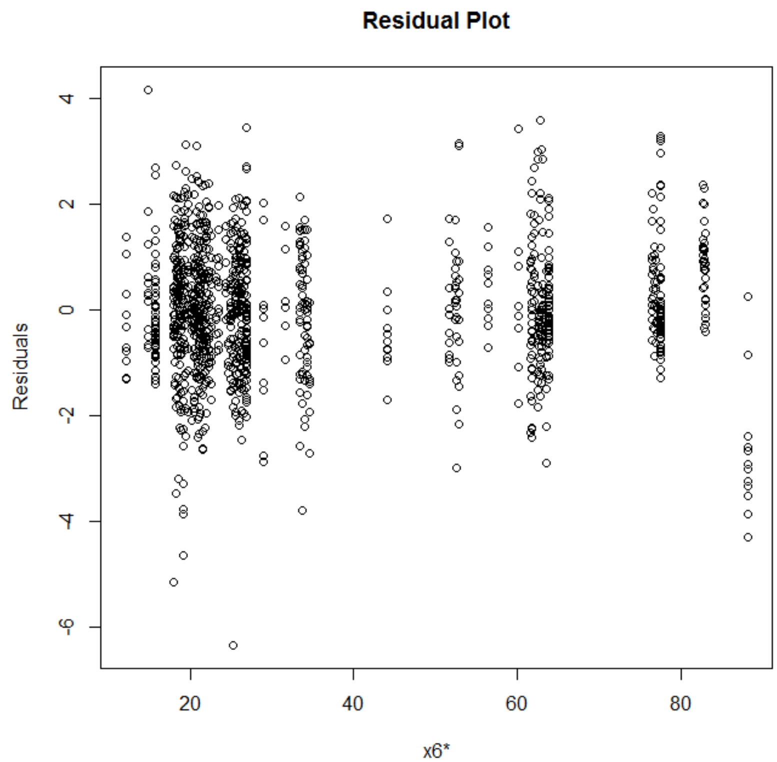
Residual Plot
Residuals
x2*
4
2
0
-2
-4
-6
0
5
10
15

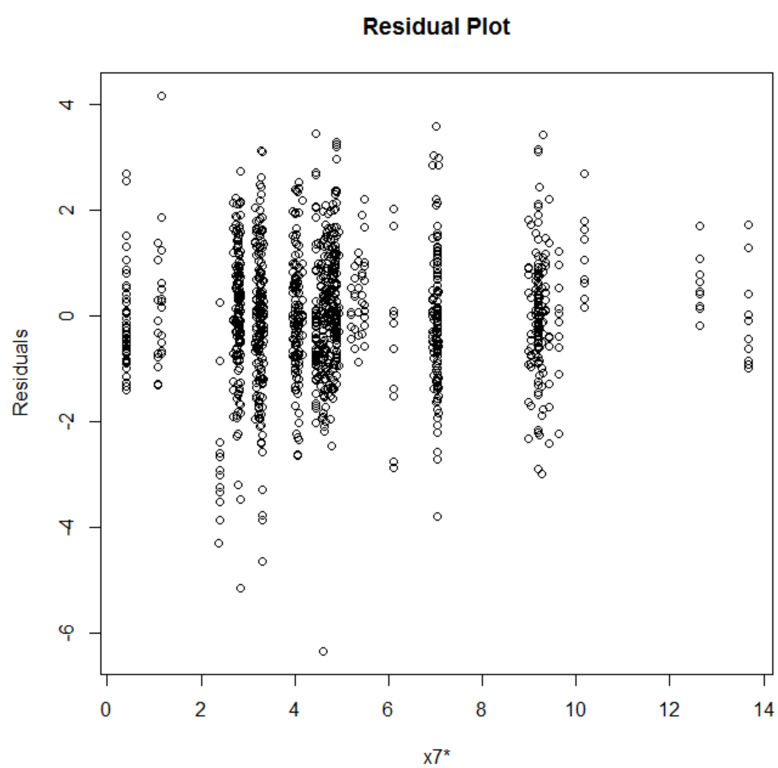


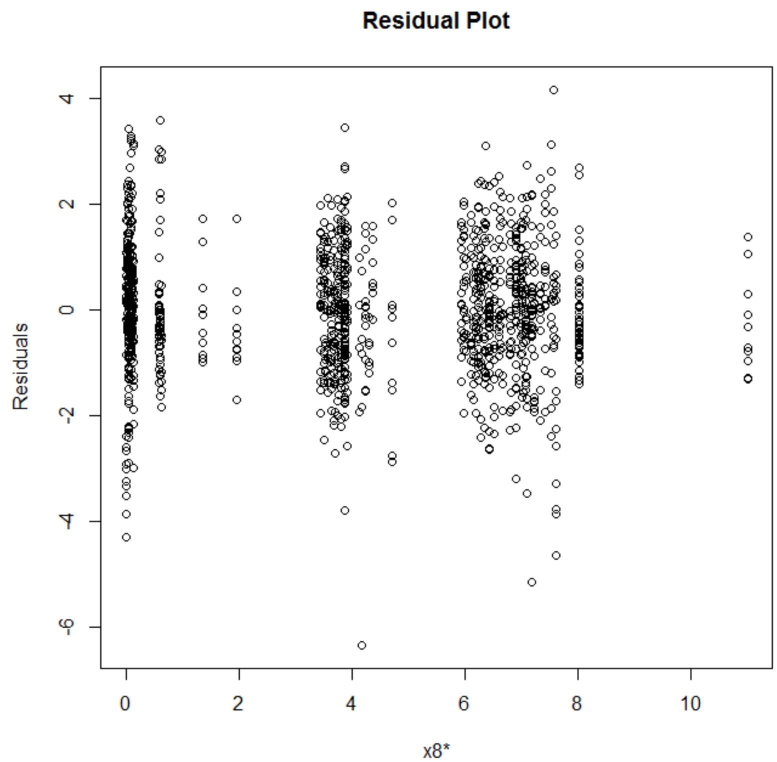
Residual Plot
Residuals
x3*
4
2
0
-2
-4
-6
0
5
10
15

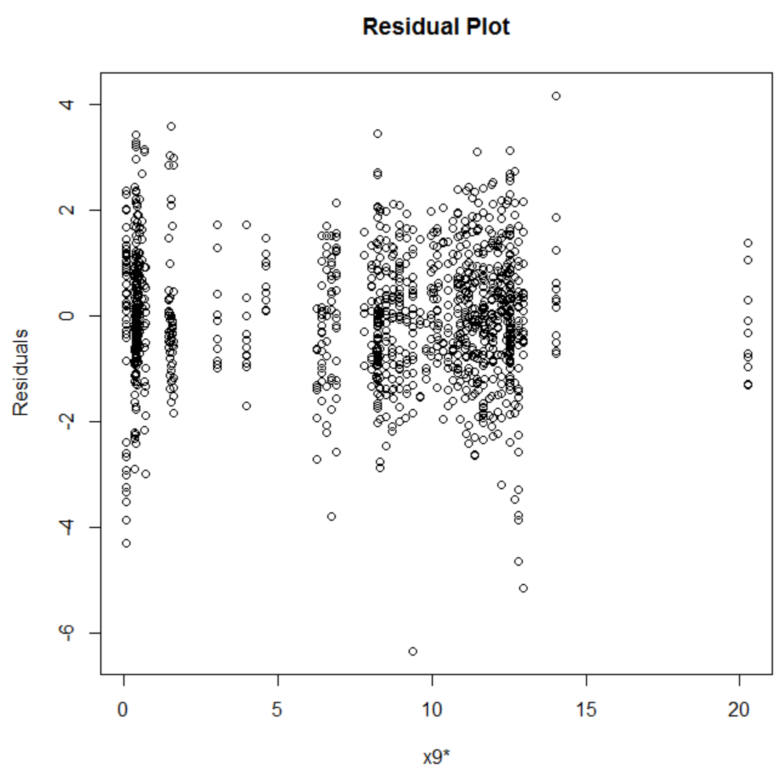

Residual Plot
Residuals
x4*

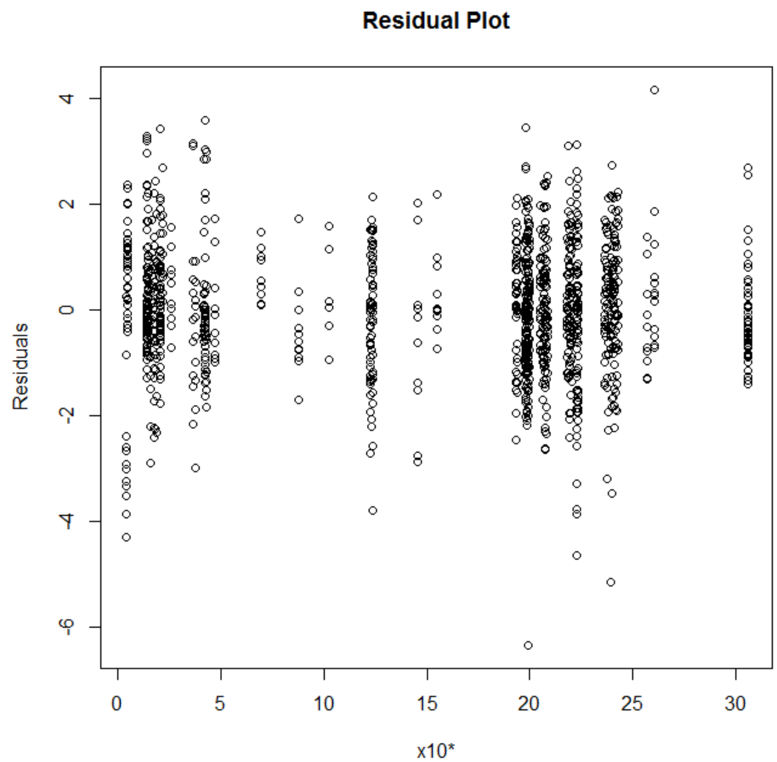

Residual Plot
Residuals
x5*

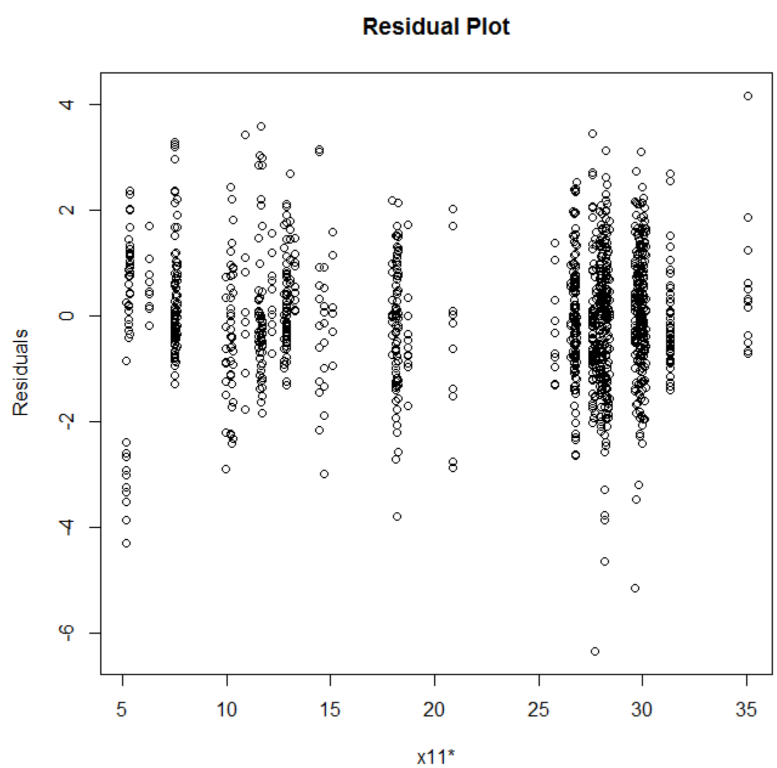

Residual Plot
Residuals
x6*
4
2
0
-2
-4
-6
20
40
60
80

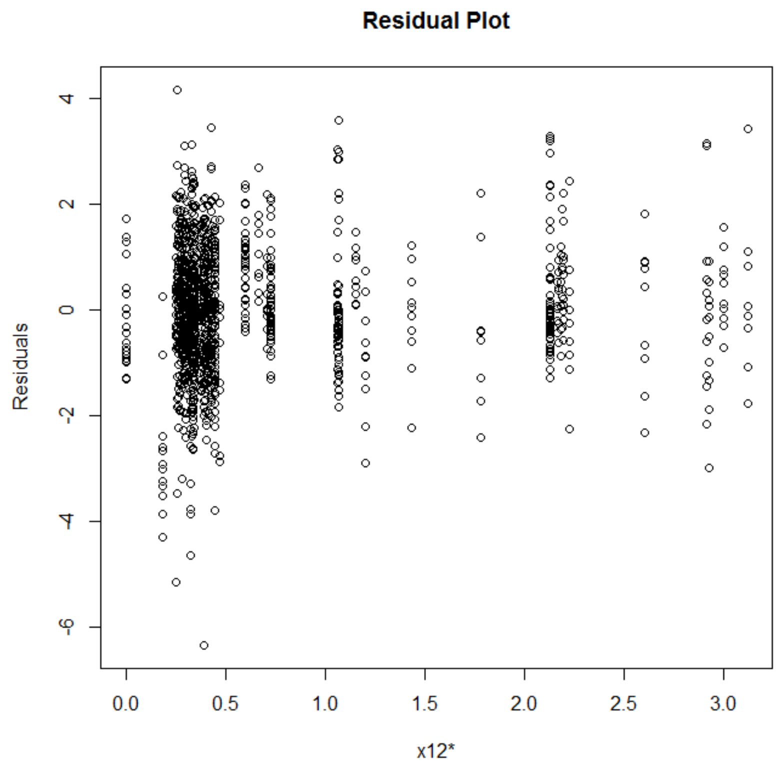

Residual Plot
Residuals
x7*
4
2
0
-2
-4
-6
0
2
4
6
8
10
12
14

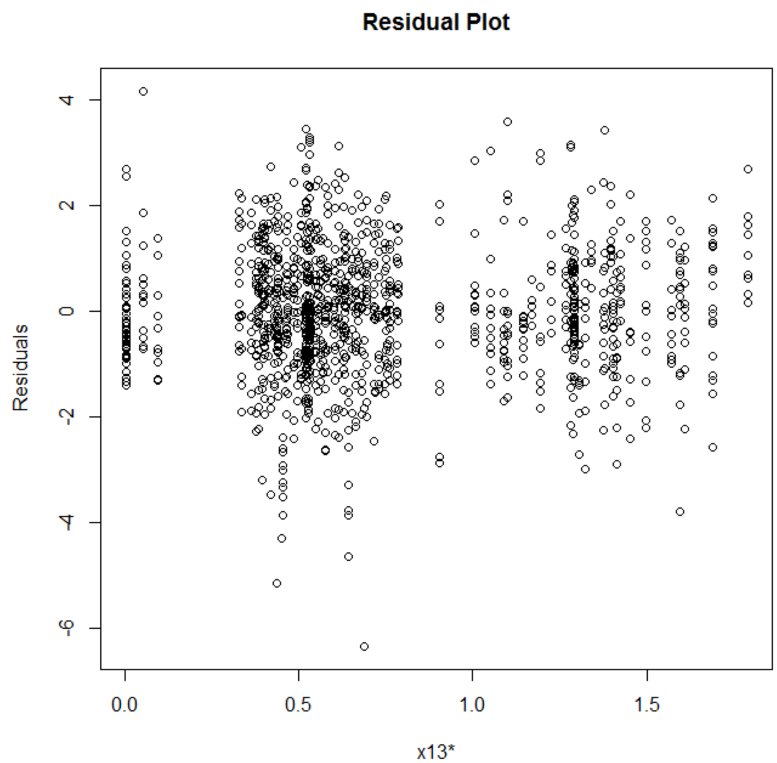

Residual Plot
Residuals
x8*
4
2
0
-2
-4
-6
0
2
4
6
8
10

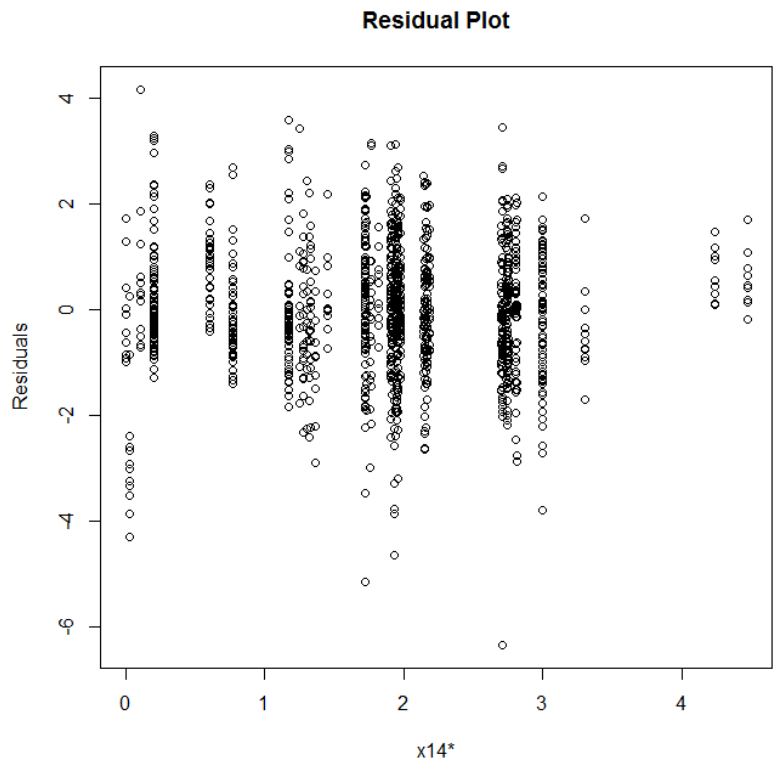

Residual Plot
Residuals
x9*
4
2
0
-2
-4
-6
0
5
10
15
20

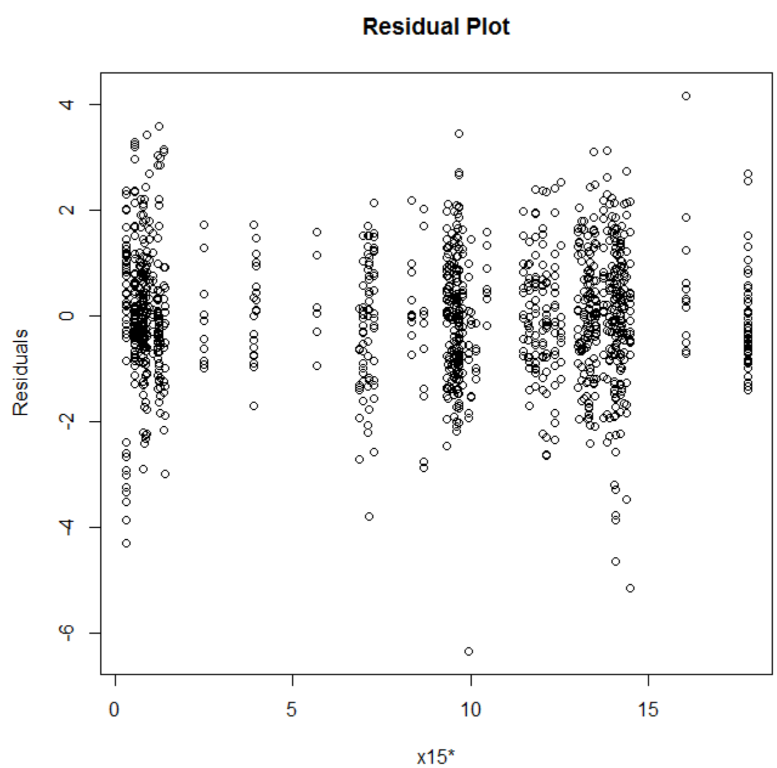

Residual Plot
Residuals
x10*

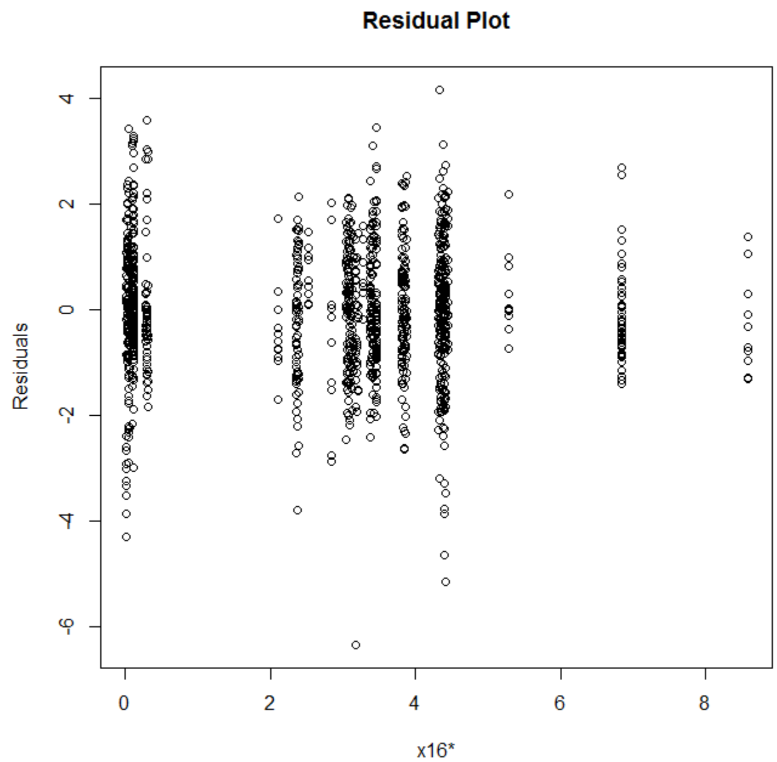

Residual Plot
Residuals
x11*

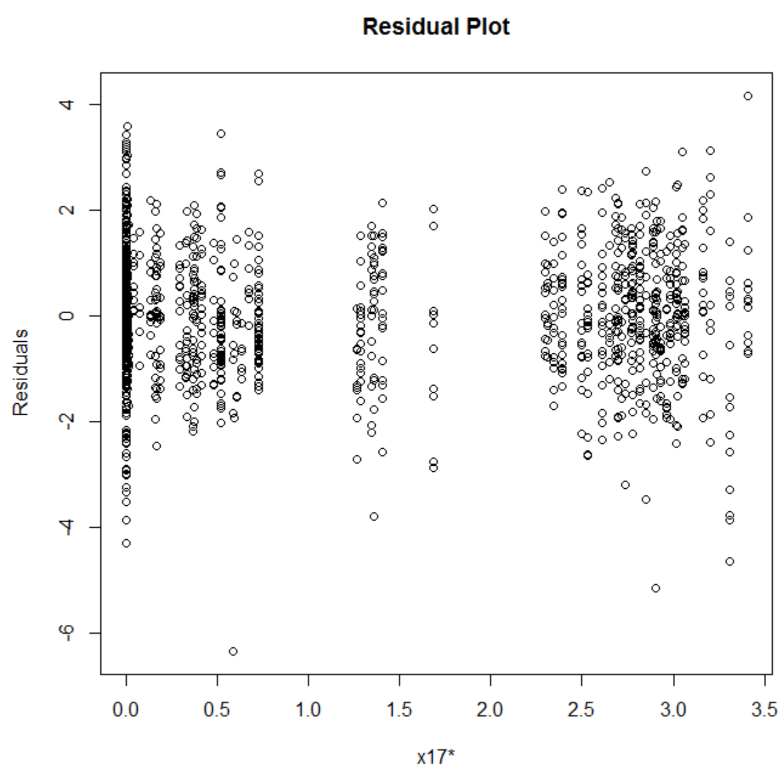

Residual Plot
Residuals
x12*
4
2
0
-2
-4
-6
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Residual Plot
Residuals
x13*
4
2
0
-2
-4
-6
0.0
0.5
1.0
1.5

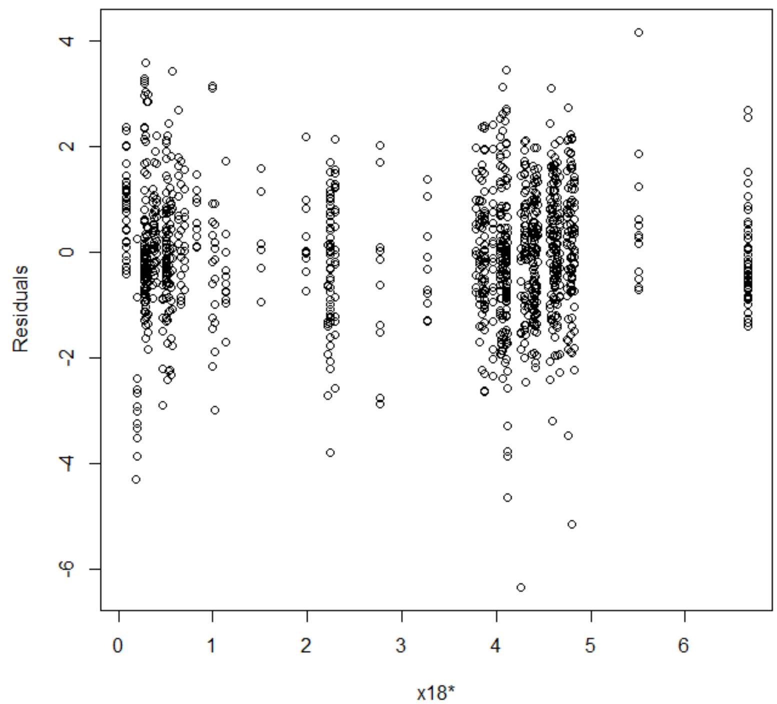

Residual Plot
Residuals
x14*
4
2
0
-2
-4
-6
0
1
2
3
4


Residual Plot
Residuals
x15*
4
2
0
-2
-4
-6
0
5
10
15

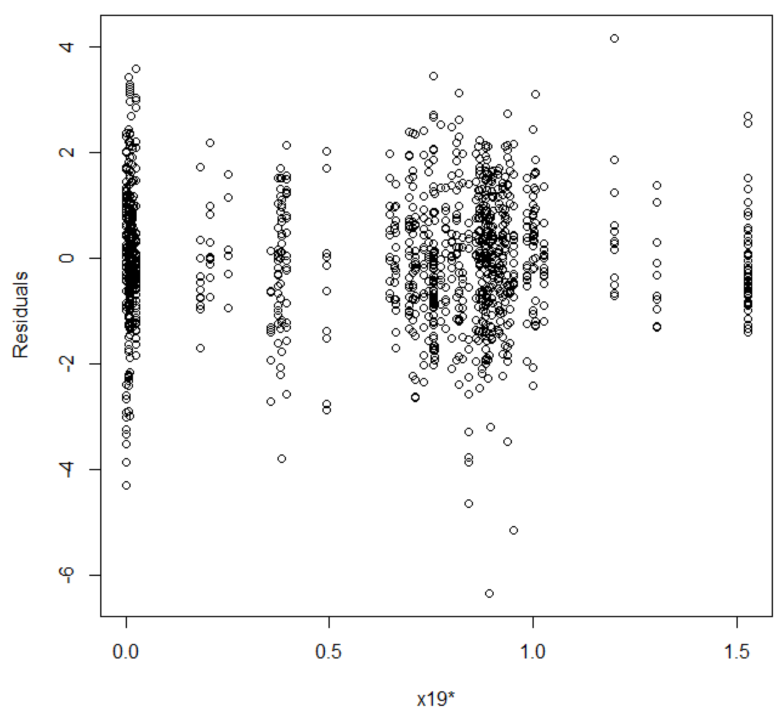

Residual Plot
Residuals
x16*
4
2
0
-2
-4
-6
0
2
4
6
8

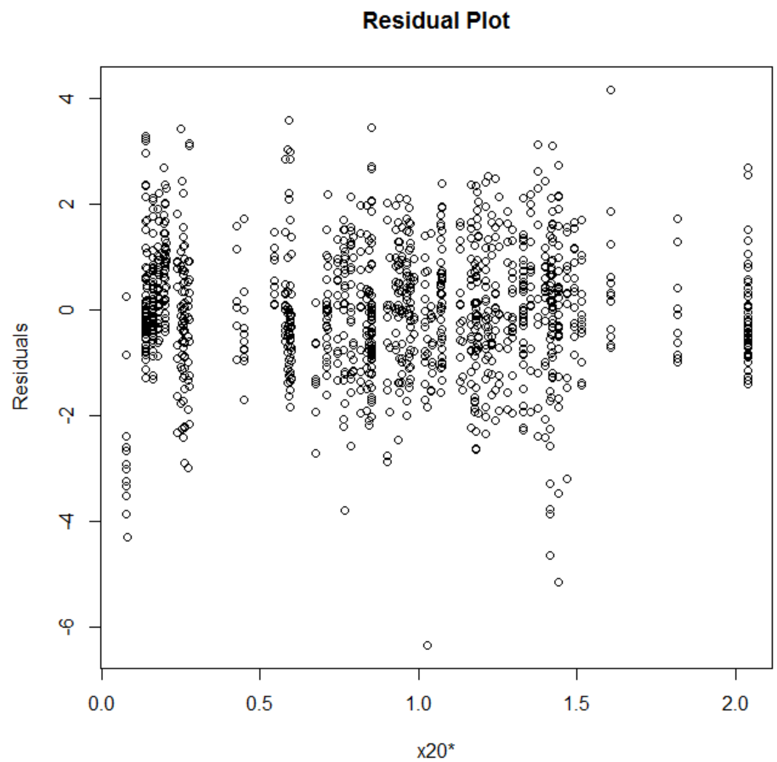

Residual Plot
Residuals
x17*
4
2
0
-2
-4
-6
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

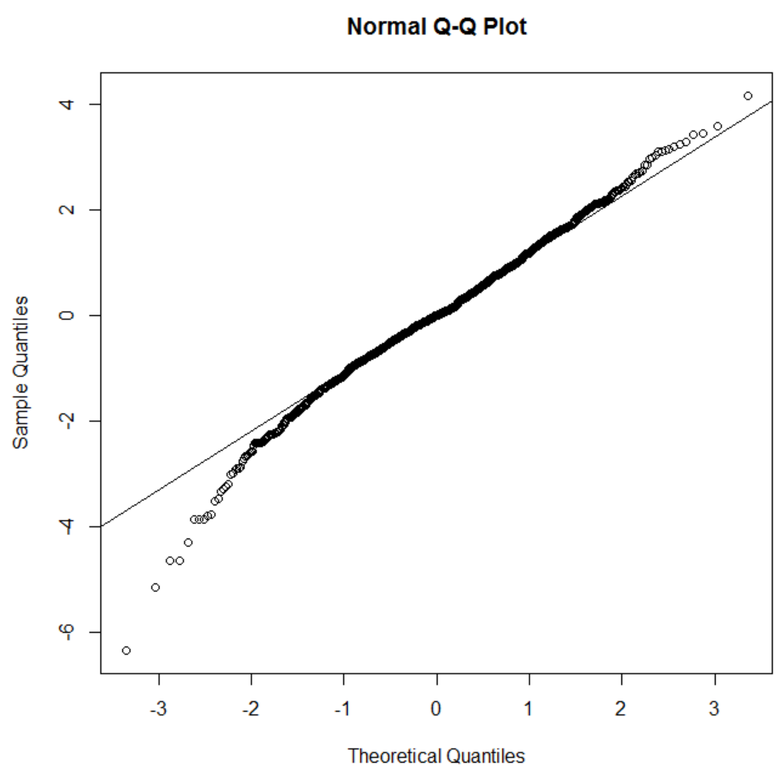
Residual Plot



Residual Plot




Residual Plot
Residuals
x20*
4
2
0
-2
-4
-6
0.0
0.5
1.0
1.5
2.0


Normal Q-Q Plot
Sample Quantiles
Theoretical Quantiles
4
2
0
-2
-4
-6
-3
-2
-1
0
1
2
3

APPENDIX C: REGRESSION MODEL OUTPUT RESULTS

Note: Results shown below are from R Statistical software analysis. Some were also run in SPSS to provide a clean output figure (see **Figures 4** through **6**).

Figure 1: Linear Regression Model with Wet Sampling Condition (x1d2), Combined Permits (x2+x3), & Combined Residential (x18+x19)

```
> summary(lm(logY~x1d2+x2.x3+x18.x19))

Call:
lm(formula = logY ~ x1d2 + x2.x3 + x18.x19)

Residuals:
    Min      1Q  Median      3Q     Max 
-5.6798 -0.7136  0.1387  0.9262  4.2081 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  4.57614    0.09342  48.983   <2e-16 ***
x1d2         2.17503    0.09981  21.792   <2e-16 ***
x2.x3       -0.01032    0.00603  -1.712   0.0872 .  
x18.x19      0.19536    0.02110   9.259   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.513 on 1238 degrees of freedom
Multiple R-squared:  0.4167,    Adjusted R-squared:  0.4153 
F-statistic: 294.8 on 3 and 1238 DF,  p-value: < 2.2e-16

> vif(fit)
    x1d2    x2.x3  x18.x19 
1.169776 1.166225 1.348878 
```

Figure 2: Linear Regression Model with Wet Sampling Condition (x1d2), Combined Permits (x2+x3), & Total Impervious Surface (x15)

```
> summary(lm(logY~x1d2+x2.x3+x15))

Call:
lm(formula = logY ~ x1d2 + x2.x3 + x15)

Residuals:
    Min      1Q  Median      3Q     Max 
-5.7202 -0.6913  0.1499  0.9201  4.2268 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept)  4.659933   0.090963  51.229   <2e-16 ***
x1d2         2.187489   0.100940  21.671   <2e-16 ***
x2.x3       -0.015220   0.005927  -2.568   0.0103 *  
x15          0.075183   0.008832   8.512   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.52 on 1238 degrees of freedom
Multiple R-squared:  0.4108,	Adjusted R-squared:  0.4093 
F-statistic: 287.7 on 3 and 1238 DF,  p-value: < 2.2e-16

> vif(fit)
    x1d2    x2.x3      x15 
1.184470 1.115216 1.309583 
```

Figure 3: Linear Regression Model with Wet Sampling Condition (x1d2), Combined Permits (x2+x3), & Total Developed Land Cover (x8+x9+x10+x11)

```
> summary(lm(logY~x1d2+x2.x3+x8.x9.x10.x11))

Call:
lm(formula = logY ~ x1d2 + x2.x3 + x8.x9.x10.x11)

Residuals:
    Min      1Q  Median      3Q     Max
-5.7103 -0.7144  0.1356  0.9401  4.1976

Coefficients:
               Estimate Std. Error t value Pr(>|t|)
(Intercept)    4.454224   0.106248  41.923   <2e-16 ***
x1d2           2.156042   0.101205  21.304   <2e-16 ***
x2.x3         -0.014768   0.005893  -2.506   0.0123 *
x8.x9.x10.x11  0.017441   0.001938   8.999   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.515 on 1238 degrees of freedom
Multiple R-squared:  0.4146,    Adjusted R-squared:  0.4131
F-statistic: 292.2 on 3 and 1238 DF,  p-value: < 2.2e-16

> vif(fit)
         x1d2         x2.x3 x8.x9.x10.x11
     1.198446      1.109957      1.318548
```

Figure 4: Factor Analysis Variance Explained

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	11.449	63.603	63.603	11.449	63.603	63.603	11.329	62.938	62.938
2	2.061	11.452	75.056	2.061	11.452	75.056	1.910	10.612	73.550
3	1.506	8.368	83.424	1.506	8.368	83.424	1.777	9.874	83.424

Figure 5: Factor Analysis Regression Coefficient Results

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	2.573	.022		118.846	.000
	REGR factor score 1 for analysis 1	.393	.022	.457	18.143	.000
	REGR factor score 2 for analysis 1	-.044	.022	-.052	-2.051	.040
	REGR factor score 3 for analysis 1	.026	.022	.030	1.196	.232

a. Dependent Variable: log(y)

Figure 6: Factor Analysis Regression Model Results

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.461[a]	.213	.211	.763041180000000

a. Predictors: (Constant), REGR factor score 3 for analysis 1, REGR factor score 2 for analysis 1, REGR factor score 1 for analysis 1

b. Dependent Variable: log(y)

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