SUITABLE GROUNDWATER MANAGEMENT:
EQUITY IN THE NORTH CAROLINA CENTRAL COASTAL PLAIN, U.S.A.

By

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Coastal Resources Management

ABSTRACT:

The purpose of this research is to assess the success of a regulation based on aquifer conditions, while testing a new approach for groundwater assessment and management that incorporates equity. Equity is often synonymous with fairness. By assessing the success of a pre-existing regulation and applying equity to a new approach to management creation, water resources are viewed as a multi-faceted, interconnected system.

Citing concerns of falling water levels, low well yields and salt water intrusion in the Cretaceous aquifers of eastern North Carolina, the North Carolina Department of Environmental Quality enacted a protective and rigorous management strategy. The strategy, based on observed water levels, adopted a single dimensional approach to address aquifer protection. Many stakeholders deemed this approach as an unfair and inequitable strategy that did not consider the multiple, often conflicting criteria involved with managing a shared natural resource. The perceived lack of equity created conflict and opposition to collaborative efforts to sustain the Cretaceous aquifers.

Moving beyond the traditional groundwater management concepts of safe yield, sustainability, and resilience, this research incorporates equity into the evaluation, allocation and management of groundwater systems. Using the CCPCUA in eastern North Carolina, U.S.A. as a case study, an equitable groundwater management approach is assessed. Although many natural resource researchers recognize the value equity, the literature lacks a framework for groundwater equity. This research begins by exploring basic equity concepts and proposing an equity framework that is applicable for management. By applying social-psychological and socio-legal concepts, the research explores how equity can contribute to acceptable policy creation. Lastly, the research explores a multi-criteria decision analysis tool, Suitability Analysis, which identifies areas most suitable to withstand changes in management strategies. This allows for a comparison of the results of a management strategy based on the physical conditions of an aquifer to one based on equity.

The research suggests that an approach to groundwater management based on equity criteria can: 1) contribute to policy development and policy strategies that stakeholders find transparent and acceptable, and 2) identify specific areas of suitability and vulnerability to changes in groundwater withdrawals. Thus, the inclusion of equity not only provides a framework for creating adaptive groundwater management strategies but contributes to sustainable aquifers and societies. This solution features early stakeholder involvement and multi-criteria assessments of the resource.

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A Dissertation

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by

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DEDICATION

I dedicate this dissertation to those who have helped me throughout the years.

To my daughters and son-in-law: Jessie Hollingsworth, Rachel and Will Jonas, and Allyn Hollingsworth, who kept me happy and sane. You are daily inspirations. My love and thanks.

To my parents: Jim Klein and Helen Klein, who taught me anything is possible with enough grit, determination and confidence.

And to my co-advisors, Drs. Alex K. Manda and Richard S. Spruill and who kept me going, while continually challenging me. If I have seen further, it is by standing on the shoulder of giants (Sir Isaac Newton). My thanks and admiration.

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1: INTRODUCTION TO SUITABLE GROUNDWATER MANAGEMENT: EQUITY IN THE NORTH CAROLINA CENTRAL COASTAL PLAIN, U.S.A.

1.1: Introduction

The United Nations (UN) proclaimed 2003 to be the International Year of Freshwater. At the same time, the UN declared the decade from 2005 to 2015 the “International Decade for Action, Water for Life”, emphasizing the crucial role water plays in sustainable development and human health (http://www.un-documents.net/a58r217.htm). Accessible potable water is at the forefront of the agenda for many international organizations as an imperative to global health. Yet, sustainable groundwater resources remain threatened by overexploitation and contamination due to increasing human, urban, industrial and agricultural development, and climate change. Globally, population growth and mismanagement of water resources have been responsible for degrading groundwater resources (e.g., Heath and Spruill, 2003; Anisfeld, 2010; Gleeson et al., 2010; Nelson, 2012) which have threatened the accessibility and sustainability of potable water.

Central to the idea of accessible and sustainable potable water is equity. Fundamentally, the management goal for any natural resource is the protection of that resource for the beneficial and sustained use by all end users. By definition, finite resources are problematic in their inequitable and limited availability. Resource management becomes an issue of integrating needs over commonly held assets, with unregulated use of finite resources prone to “The Tragedy of the Commons” (Hardin, 1968). Unless solutions are deemed fair and equitable by all involved, the commonly shared and finite resource becomes misused and depleted. Water resource managers face a “commons” dilemma which, if unregulated, allows individuals or entities to act according to their self-interest, with little regard for how that resource is protected, shared or equitably allocated. Effective water use includes adaptive management to prevent exploitation of this “commons” resource, otherwise the resource is degraded, and societal needs are not met (Klein et al., 2014). Managers who do not include equity or adapt water strategies to the ever-changing multi-dimensions of water resources cannot successfully manage the demands imposed on water resources (Dietz et al., 2003).

This research explores issues of equity in groundwater management. Using the Central Coastal Plain Capacity Use Area (CCPCUA) as a case study, the research investigates how equity principles apply to procedural justice, groundwater management and a multi-dimensional equity model. The CCPCUA is a fifteen-county area in eastern North Carolina (Figure 1) in which groundwater withdrawals are closely regulated and monitored to maintain sustainable groundwater resources.

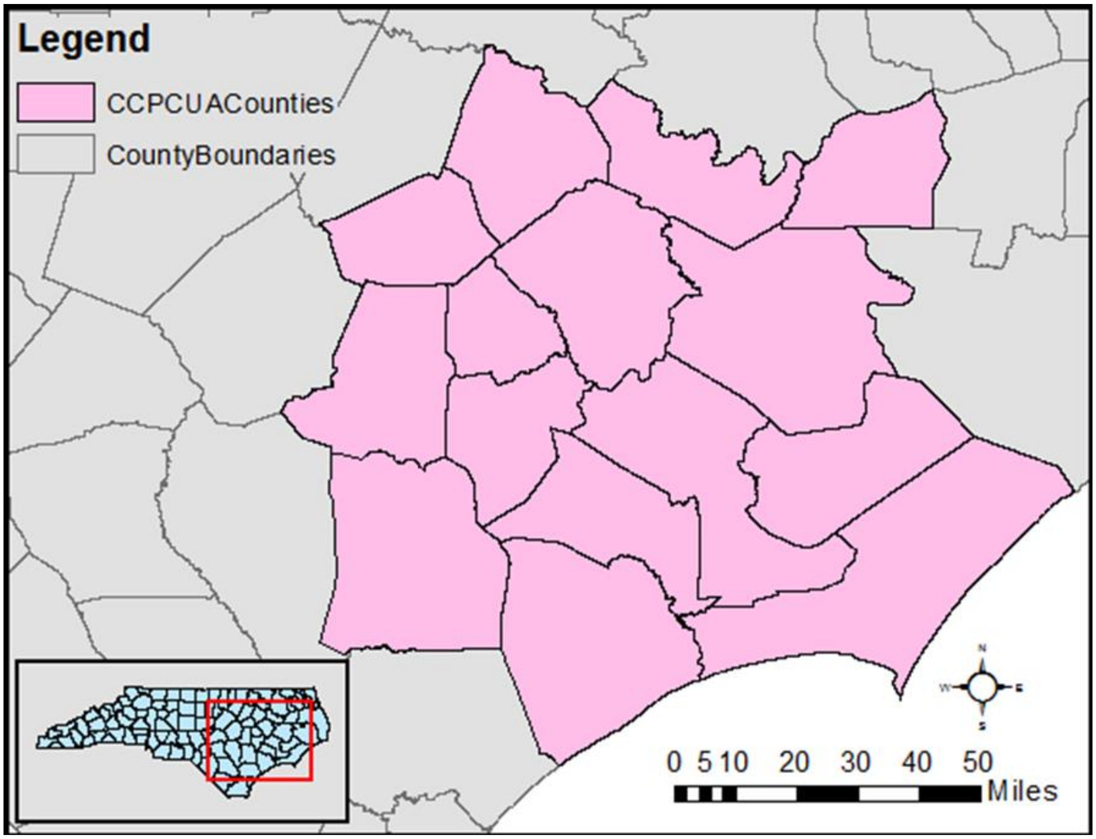

Figure 1. Fifteen Counties of the CCPUA.

For the purposes of this research the definition of sustainability is taken from the 1987 United Nations (UN) Brundtland Report (1987). The UN report defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations General Assembly Resolution A/42/427)."

1.2: Background

The aquifers underlying the CCPCUA counties are composed of a sequence of marine and non-marine, eastward dipping and thickening sedimentary units that range in age from the Cretaceous to the Quaternary, and overly a Paleozoic basement (Figure 2).

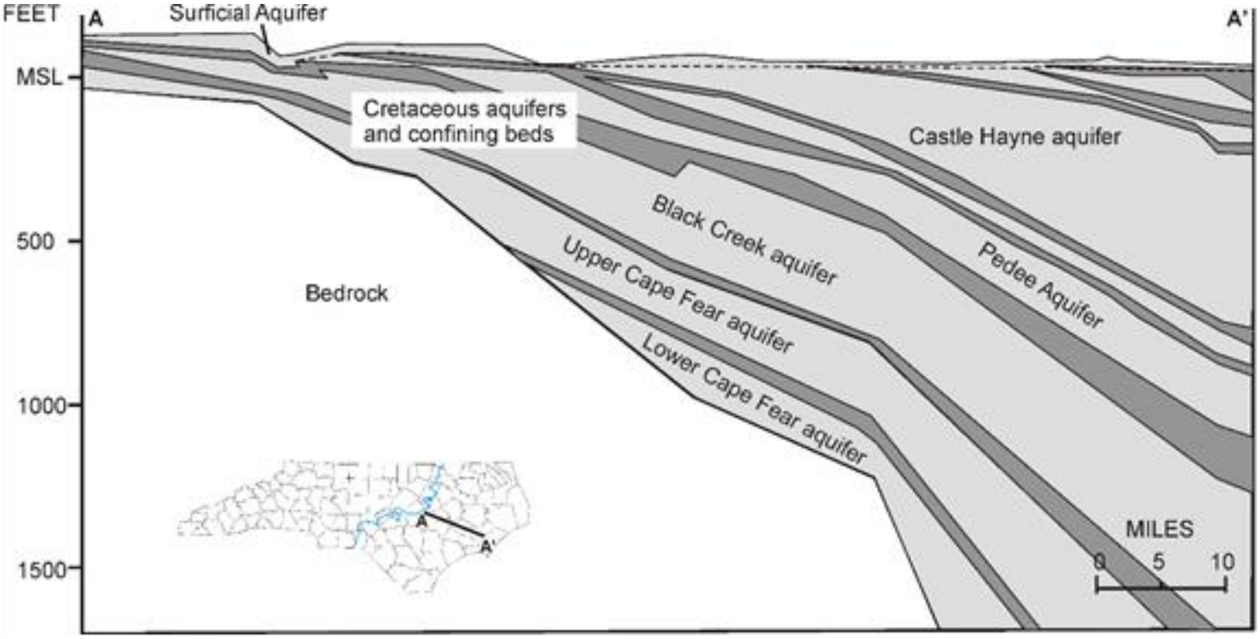

Figure 2. West-East structural cross-section, after Geise et al., 1997.

At its thickest, the sedimentary section exceeds 1,500 feet (Lautier, 2006). Historically, eastern North Carolina has relied on these aquifers as a source of readily available, high quality water. However, this heavy reliance on the Eocene (i.e., the Castle Hayne aquifer) and Cretaceous aquifer systems (primarily the Black Creek and Upper Cape Fear aquifers) coupled with limited foresight and mismanagement have severely degraded the groundwater resources of eastern North Carolina (Heath and Spruill, 2003).

1.3: Problem statement

This research is designed to investigate and understand the CCPCUA aquifer system from the standpoint of equity, viewing water resources allocation and management as an interconnected system of physical and socio-economic inputs. Existing management strategies based on the concept of “safe yield” take a single dimensional perspective to address the problem. Through an evaluation of the evolution of groundwater management concepts (e.g., safe yield, sustainability, resilience), alternative evaluation concepts are employed to create adaptable management policies for equitable groundwater management. This project will use the CCPCUA in eastern North Carolina, U.S.A. as a case study to assess the value of new tools to develop equitable groundwater management strategies. Pairing the natural sciences, which inform policy decisions, with social sciences, which drive policy, the new tools integrate the multi-dimensions involved with groundwater management into the field of socio-hydrology (Sivapalan et al., 2012).

Between 1970 and 1990, the total population in the CCPCUA counties increased by 20% from 695,598 to 834,718 inhabitants (http://www.census.gov), which led to an escalation in water demand and groundwater withdrawals and threatened the sustainability of aquifers within the CCPCUA (Heath and Spruill, 2003). As populations increased, groundwater withdrawals increased, causing a substantial decline in the groundwater levels in the Cretaceous aquifers. The declining water levels (as much as 2.4 m/7.9 feet per year), large cones of depression, saltwater intrusion, and low well yields in the Cretaceous aquifers (Giese et al., 1997; Heath and Spruill, 2003; Lautier, 2006) represented aquifers that could no longer support the water needs for the area. Intervention, in the form of aggressive management strategies, was needed to restore the health of the threatened aquifers.

Innovative procedural justice concepts such as social psychological (substantive, procedural and emotional) and socio-legal (justice) were incorporated into a rulemaking process involving a stakeholder participation group. The group's task was to craft rules to sustainably manage the endangered groundwater resources of the eastern North Carolina Coastal Plain. In 2002, the North Carolina legislature accepted the regulation developed by the stakeholder group and enacted the CCPCUA rule to manage the degrading Cretaceous aquifers. The 2002 regulation used the Water Use Act of 1967 (http://www.ncwater.org), which empowered the state environmental regulatory agency, the North Carolina Department of Environment and Natural Resources (NCDENR), to form Capacity Use Areas to monitor and regulate aquifers and surface water bodies. Under the authority of the Water Use Act of 1967, the 2002 CCPCUA rules developed a new capacity use area, required withdrawal permits and registrations, and assigned phased groundwater pumping reductions over a 16-year period.

The water levels began to respond positively following the completion of the first phase of reductions. Other gauges of the sustainability of the aquifer system (reduction in the cone of depression, slowing and in some cases the reversal of salt water intrusion, improved yields) reflected the success of the regulation by reversing the degradation of the Cretaceous aquifers. The successful aquifer response was accomplished by imposing reductions based on the condition of the aquifers at the end of the 20th century. However, limited considerations were given to hydrogeologic characteristics, needs, population, available developed water sources, availability of alternate water sources, or the financial ability to develop alternate water sources. With the benefit of hindsight, this research, in part, examines the need to impose rigorous, across the board reductions on the stakeholders based on a single criteria (water levels). In addition, the research looks at the regulation from the standpoint of equity, delving into how to craft a regulation based on equity by considering multiple criteria. This research moves management schemes beyond a water balance formula (recharge keeping pace or exceeding withdrawal) and demonstrates an alternate, integrated water management strategy which considers multiple physical, social, spatial and temporal criteria.

1.4: Dissertation goals

Using the following recommendations of Kelly et al. (2013), the case study of the CCPCUA regulation provides a unique opportunity to examine the evolution and possible future adaptations to a successful groundwater management regulation.

1. Describe the systems. This includes both the socio-economic and the physical systems.
2. Improve social learning or learn from past patterns of social interactions.
3. Advance adaptive prediction tools.

Incorporating these three recommendations, this research strives to develop new transparent tools to build policy and decision-making strategies.

As such, the goals of this research are to (a) summarize the evolution of groundwater management strategies in the literature, (b) incorporate social and organizational psychology, and socio-legal studies to evaluate how procedural justice and public participation play major roles in resolving groundwater resource management problems (c) create adaptive prediction tools through backcasting, (d) include ideas from different disciplines to develop new approaches to groundwater management, (e) integrate the individual socio-economic and hydrological sciences into groundwater management, and (f) compare the results of the CCPCUA regulation sixteen years after its inception to other tools that incorporate social and hydrologic systems.

The North Carolina Division of Water Resources (NCDWR) conducts periodic assessments, overseen by the North Carolina Environmental Management Commission, as required by 15A NCAC 2E .0503(7), that consider the rate of increase, decrease or stabilization of the aquifer's water levels and the advance or retreat of salt water intrusion. Typically, this type of review process considers the natural sciences, yet, resource issues are multi-dimensional and must therefore consider factors from fields outside of the natural sciences. The Intergovernmental Panel on Climate Change (IPCC) has repeatedly stressed the importance of conducting interdisciplinary studies for the impacts of climate change (http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap3_FGDall.pdf). This research proposes to follow the IPCC recommendation and apply those recommendations to integrate the multiple physical and social dimensions into the groundwater management dialogue.

1.5: Dissertation objectives and research questions

The research poses the question to what extent the CCPCUA regulations consider equity. The specific objectives used to answer this question include the following:

Objective 1: To evaluate the success of the Central Coastal Plain Capacity Use Area regulation.

- Research Question 1a: How effective was the application of procedural justice concepts in creating groundwater management policy?
- Research Question 1b: How did stakeholder participation in the rulemaking process result in groundwater management policy and changes to groundwater characteristics?

Objective 2: To evaluate alternate groundwater management approaches that incorporate physical and social aspects for equitable groundwater allocation.

- Research Question 2a: How have groundwater management theories evolved from safe yield to an equity-based measure?
- Research Question 2b: To what extent did the 75% reductions mandated by the Central Coastal Plain Capacity Use Area regulation consider equity?

1.6: Structure of the dissertation

This dissertation is composed of six chapters and three appendices. Several chapters, or portions of chapters are independent, stand-alone articles. As a result, there is some duplication of material, especially in the introductory and background sections. Most of the chapters have been submitted for publication or will be submitted for publication in peer review journals. Each of the chapters includes their own sections on literature review, methodology, and references, as such there will not be an independent, comprehensive chapter devoted to these items. Each chapter addresses the research question of "to what extent did the 75% reductions mandated by the CCPCUA consider equity?" The protocol to answer this basic research question is shown in Figure 3. Each chapter tackles the research question by looking at a procedural, management or conceptualized model of equity. The research delves into four important ideas: the need to 1) include stakeholders early in the management planning stage, 2) appreciate the evolution of the management processes, 3) describe the links between the social, economic and hydrologic systems, and 4) create innovative assessment tools for groundwater management strategies.

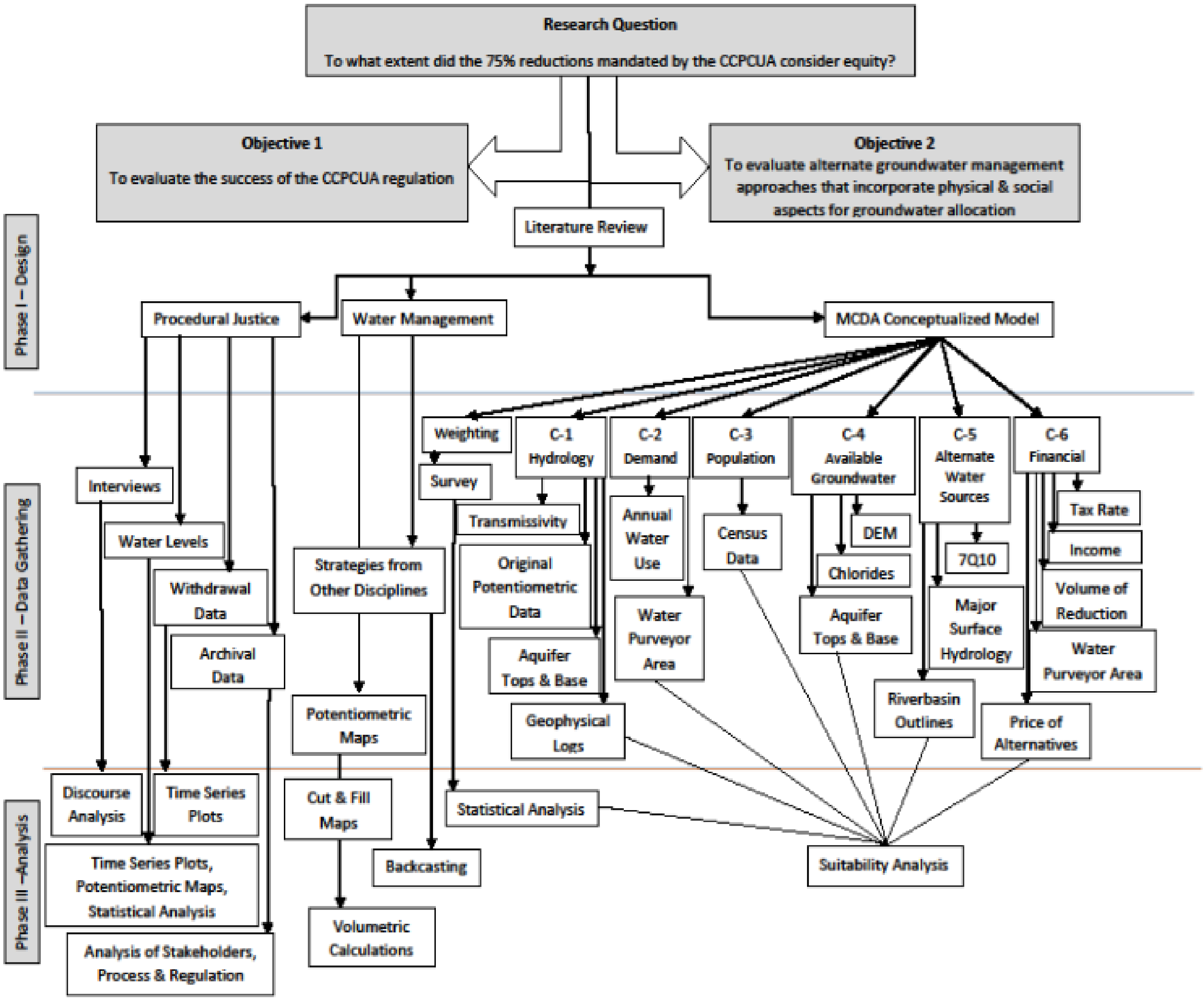

Figure 3. General Protocol for creating the equity model.

Chapter 2 lays the groundwork for the central theme of this research, equity. Although the idea of equity is fundamental to the allocation of natural resources there is no comprehensive framework for equity. Chapter 2 includes a suggested equity framework based on one established for natural resources co-management. Also introduced is the idea of developing equitable groundwater management strategies using multi-criteria analyses.

The article which makes up Chapter 3, Procedural Justice and the Creation of the Central Coastal Plain Capacity Use Area Regulation is included in its entirety. Entitled "Rescuing degrading aquifers in the Central Coastal Plain of North Carolina (USA): Just process, effective groundwater management policy, and sustainable aquifers", the article was published in Water Resources Research in 2014 and addresses Research Question 1a: How did stakeholder participation in the rulemaking process result in groundwater management policy and changes to groundwater characteristics? It discusses how a stakeholder group led to the application of procedural justice theory and how that process resulted in a regulation which stakeholders found fair and one with which they were able to comply. An analysis of the CCPCUA development process shows how stakeholder participation in a process they deemed fair resulted in regulations that are understandable and relatively easy to administer for users and regulators. In addition, an examination of the CCPCUA process illuminates how public participation resulted in effective strategies to ensure long-term, sustainable groundwater use.

Chapter 3 continues by answering Research Question 1b: How did stakeholder participation in the rulemaking process result in groundwater management policy and changes to groundwater characteristics? The CCPCUA case study shows how the regulation crafted by the stakeholder committee achieved its charter goal of improving and maintaining groundwater quantity and quality. A study of groundwater levels in the Black Creek and Upper Cape Fear aquifers illustrates how water levels in the Cretaceous aquifers changed in the CCPCUA after implementation of the area rules. This chapter demonstrates that the stakeholders created a regulation that not only "rescued" the stressed aquifers, but also encouraged diversified and alternate sources of water, conjunctive water use, interconnections and investment in alternate and new technologies.

Chapter 4, Adaptive Management and the Continuing Journey Away from Safe Yield, includes the article "Refining management strategies for groundwater resources" and is included in its entirety, as published in Hydrogeology Journal in 2014. Chapter 3, in part, addresses

Research Question 2a: How have groundwater management theories evolved from safe yield to an equity-based measure, as it traces the evolution of groundwater management approaches and supports the proposal for adopting adaptive and equitable management strategies.

Chapter 4 continues by exploring the ultimate goals for resource managers, sustainability and resilience. These ideals can be achieved by re-examining basic groundwater management norms and include additional strategies to maintain variously scaled projects, over both short and long-time scales while incorporating changing environmental, social and economic conditions. Backcasting is a suggested approach through which managers envision what the aquifers should look like in the future and create strategies to reach that vision. The research also presents management strategies from other disciplines (e.g. business) and illustrates how they can be applied to water resource management. Because the CCPCUA regulation was based on the concept of safe yield, it is instructive to review the ongoing conversation about the meaning and usefulness of the concept. This research traces the evolution of safe yield and other groundwater management strategies to compare how different management theories have influenced the development of groundwater policy.

The research goes on to consider how adaptive management can support an approach that incorporates the concept of equity. The idea of creating natural resource strategies through the focus on equity reflects the evolution of management thinking through a transition from safe yield, sustainability and resilience. Various techniques have been proposed to create fair (equitable) water policy, including hydro-sociology, social-ecological systems, water resource management, integrated water resource management, adaptive water management, hydro-economic modelling, coupled human natural systems, and socio-hydrology. These approaches are investigated in Chapter 3. By considering equity, the norms of groundwater management are redirected, changing how managers view, discuss and define the stresses on an aquifer.

In Chapter 5, Research Question 2b addresses the central theme of the dissertation: To what extent did the 75% reductions mandated by the Central Coastal Plain Capacity Use Area regulation consider equity? Chapter 5, A Comparison of the Outcomes of the 2002 Central Coastal Plain Capacity Use Regulation to an Equity Based Multi-Criteria Decision Analysis, compares the results of the 2002 CCPCUA regulation to a strategy based on equity and built on a multi-criteria and suitability approach. Geographical Information System analyses (GIS), adaptive management, and equity concepts are merged in a Suitability Analyses (SA) to create an aquifer analysis tool that employs a comprehensive, quantitative evaluation mechanism. This type of alternate approach allows for equitable allocation of groundwater resources because it takes a multi-criteria view of resource management.

The heart of Chapter 5 uses the ArcGIS based Suitability Analysis tool (SA) to determine the areas most vulnerable to changes in water withdrawals and suggests areas most suited for different levels of withdrawal, all while considering both the socio-economic characteristics of the CCPCUA and the physical characteristics of the underlying aquifers. With the results of the Suitability Analysis completed, Chapter 5 presents a comparison of the outcomes of the two different management approaches; one based solely on the physical conditions at the time of inception and one based on multiple criteria. The evaluation compares three scenarios: 1) without adoption of the withdrawal reductions as mandated by the CCPCUA, 2) with full compliance of the tiered reductions as mandated by the CCPCUA, and 3) adoption of the MCDA withdrawals.

The suitability analysis, based on multi-criteria analysis, explores criteria deemed important for resource planning and management. Based on guidelines set forth by the UN

(1997), Chapter 5 incorporates six equity criteria, (C1) hydrogeologic and aquifer characteristics, (C2) stakeholder demands, (C3) population dependent on water, (C4) availability of groundwater supply, (C5) availability of alternate water sources, and (C6) financial potential to develop alternatives. Different methodologies for creating each geospatial (thematic) layer are used. These are discussed in detail in the appendix. Chapter 5 concludes with a discussion of the effectiveness of the CCPCUA at creating an equitable regulation, by comparing an alternate management scheme developed through the suitability analysis and using the integrated equity criteria.

Chapter 6 discusses the conclusions of the research, as well as identifies research gaps, with suggestions for future work. The chapter also identifies effective evaluation tools, strategies for efficient management, and suggestions for collaborative stakeholder engagement.

Appendix A introduces the multi-criteria decision analysis process and describes the construction of the criteria thematic layers used for input into the Suitability Analysis. Because the criteria involved both qualitative and quantitative data, the preparation of each thematic layer is different. The processes of developing each layer are explained.

Appendix B contains a discussion of an important element of suitability analysis; how to assign appropriate weights to the various criteria affecting sustainable water resources. The section, Using the Analytic Hierarchy Process to weight groundwater management criteria in coastal regions, accepted for publication in the Elsevier special volume: Coastal Zone Management: Global Perspectives, Regional Processes, Local Issues, is included in the appendix as a stand-alone article. Multi-criteria decision analysis typically requires the assignment of weights to individual criteria to consider the effect each criteria has on a decision. However, when it comes to groundwater management decisions, it is not clear whether there is consensus about which criteria are the most important and to what degree various criteria differ from one another. To address this issue, the article assesses how groundwater professionals perceive the importance of various groundwater criteria, as well as how to ascribe weights to those criteria. Using the Analytic Hierarchy Process is another example of the application of analytical techniques usually employed in other disciplines to resolve groundwater management issues.

Appendix C includes a discussion of how volumetric analyses can augment water level data for determining the sustainability of an aquifer. Because the CCPCUA regulation is based on water level observations, Appendix C compares changes in water levels to changes to overall storage volumes. Using the Black Creek aquifer as a case study, this section examines if changes in water levels accurately convey the storage capacities of aquifers.

1.7: Dissertation significance

This research provides additional tools for the protection and sustainable use of aquifers by incorporating equity into groundwater management strategies. The significance of this research is as follows:

- Dissects the creation and implementation of a successful groundwater management strategy.
- Unites approaches taken from multiple disciplines for adopting adaptive and equitable management strategies.
- Develops tools for equitable allocation of groundwater resources based on the physical and social characteristics of an aquifer system applicable in other regions where groundwater is exploited.
- Applies a suitability model approach to integrate the multiple criteria that are measured in different scales.

- Evaluates the value of management concepts (e.g., safe yield, sustainability, resilience) that will elucidate how strategies have been developed and applied to manage groundwater resources.
- Augments current assessment approaches to the evaluation of the health of aquifers.
- Initiates a paradigm shift in groundwater management, de-emphasizing evaluations based on safe yield while highlighting ideas of equity and justice.
- Advances interdisciplinary work: Equity based socio-economic-hydrology.

1.8: Global implications

Incorporating equity into groundwater management has global implications and includes:

- Minimizes conflicts surrounding groundwater allocation to increase partnerships between stakeholders, government agencies and scientists.
- Strengthens cooperation among all stakeholders to improve water efficiency.
- Encourages diversified and alternate sources of water through a more realistic understanding of groundwater and human interactions.
- Attains the conflicting mandates of equitably promoting sustainable aquifers, protecting a multi-use water supply, and stimulating economic development.
- Increases societal scientific awareness.
- Assures equitable allocation of water to improve water security and water access.
- Incorporates equity tools to diffuse water conflicts among stakeholders, government agencies and scientists.

1.9: Societally related impacts

Socio-hydrology explains an action and reaction effect between the physical and social sciences (Sivapalan et al. 2012). Ultimately the impact of equitable groundwater management is measured by the impacts on society. Those impacts include:

- Increased stakeholder involvement
- Increased societal scientific awareness
- Increased partnerships
- Improved water security
- Minimization of conflicts surrounding groundwater allocation

2: EQUITY FRAMEWORK

Key Points

- Equity is a measure of fairness.
- There is no previously established framework for natural resource equity.
- Equity is linked with sustainability.
- A comprehensive framework is needed to organize the variables involved with natural resources.
- Equity is defined in terms of input and output (outcome).

Equity is a multidimensional concept that defies a universal definition (Westcoat Jr. et al., 2002; Phansalkar, 2007; Wilder, 2008; Norgaard, 2008; Ostrom, 2009, Lukasiewicz, 2017). Often synonymous with fairness and justice (Leventhal, 1980; Syme and Nancarrow, 1992; Boelens, 1998; Beder, 2000; Syme et al., 2000; Nancarrow and Syme, 2001; Westcoat Jr. et al., 2002; Perreault, 2014; Lukasiewicz, 2017), it is often characterized by inputs and outputs (Carrell and Dittrich 1978, Folger, 1986). Equity is often used interchangeably with merit, worth or assurance of needs (Lukasiewicz, 2017).

From the perspective of international watercourse law, the terms equitable, beneficial and reasonable appear interchangeably. The UN convention refers to equitable and reasonable use (UN Convention on the Law of Non-Navigational Uses of International Watercourses, 1991). Following utilitarian principles, resources are allocated for the greatest good for the greatest number of citizens, yet equity, especially in terms of allocation of resources, is subjective, for what appears to be fair to one individual or group may be perceived as unfair to another (Leventhal 1976; Walster et al., 1978; Leventhal, 1980; Ingram et al., 2008). The challenge to equitably allocate resources is to provide for increasing demands for those resources while reversing abuse to the environment (Norgaard, 2008). This is a noble goal, yet one that is difficult to construct. “The effort always is to secure an equitable apportionment without quibbling over formulas” (New Jersey v. New York, 1931). Equitable apportionment of surface waters is “a flexible doctrine which calls for the exercise of an informed judgement on a consideration of many factors” (Colorado v. Mexico, 1982). As stated by the U.S. Supreme Court, this entails a holistic, multi-disciplinary approach (Colorado v. Mexico, 1982). Equitable apportionment of groundwater must also be flexible, multi-disciplinary, and multi-dimensional.

Equity is often linked with sustainability through the idea of managing common yet competing interests and shared resources for current and future societal needs (United Nations General Assembly Resolution A/42/427, 1987; Beder, 2000; Gleick, 1998; Gleick, 2000; Westcoat Jr. et al., 2002). Issues pertaining to sustainable development of natural resources result from an imbalance and interdependence in “economic and political power” on local to global levels (United Nations General Assembly Resolution A/42/427, 1987). However, the concepts of sustainability, equity and interdependence extend beyond financial and geopolitical considerations. Although a myriad of social and physical factors also impact the equitable and sustainable management of natural resources, the various relevant disciplines are usually studied individually, without the benefit of understanding how they interact and impact each other (Ostrom, 2009; Lu, et al., 2014), with the social, political, economic, environmental sciences often competing for importance (Mollinga et al., 2007; Ingram et al., 2008; Mollinga, 2008; Lu et al., 2014). Single disciplinary analyses do not provide the large picture of complex systems (Norgaard, 2009; Ostrom, 2009; Lu et al., 2014), nor can they easily analyze associations of criteria at “different spatial and temporal scales” (Ostrom, 2009).

A comprehensive framework is needed to organize the many important variables involved with equitable management of commons natural resources (Ostrom, 2009), yet there appears to be a literature gap with respect to a standardized equity framework. This may be because equity is complex and depends on the situation, location and relationships of stakeholders with each other and with the resource (Ingram et al., 2008). It also might be because equity, with respect to water, is frequently tied to geopolitical, economic and social concerns (Bakker, 2007; Lu et al., 2014) and an imbalance of power (Phansalkar, 2007; Lukasiewicz, 2017). Yet, although an overarching equity framework does not exist, many water policy investigators incorporate elements of equity in their research (Syme and Nancarrow, 1992; Syme and Nancarrow, 1997; Boelens, 1998; Syme et al., 2000; Rogers et al., 2002; Westcoat, et al., 2002; Tisdell, 2003; Whitely and Ingram, 2008; Cai, 2008; Goff and Crow, 2014; Lu et al., 2014; Perreault, 2014).

Despite the acknowledgement by many authors that equitable groundwater governance affects ecosystems, as well as humans (Gleick, 1998; Gleick, 2000; Bakker, 2007; Fishman, 2011; Lu et al. 2014), the literature lacks a framework for groundwater equity that incorporates the management of both the social and physical concerns, simultaneously. In lieu of a previously established framework for equity, this research builds loosely on the framework established by Plummer and Fitzgibbon (2004) for natural resources co-management. The Plummer and Fitzgibbon framework is structured around the three basic components of preconditions, characteristics and outcomes. However, equity is often defined in terms of input and output (Carrell and Dittrich, 1978; Folger, 2013), therefore, for the purpose of this groundwater management research, input replaces preconditions as a component. Process replaces characteristics as the path or mechanism to achieving the equitable outcome of protecting aquifer quality and reallocation of groundwater resources. Outcome is used synonymously with output. Inputs, processes and outcomes are universal components; the specifics of each component are tailored for the CCPCUA case study yet have global applications. A new framework, adapted from the Plummer and Fitzgibbon model is shown in Figure 4.

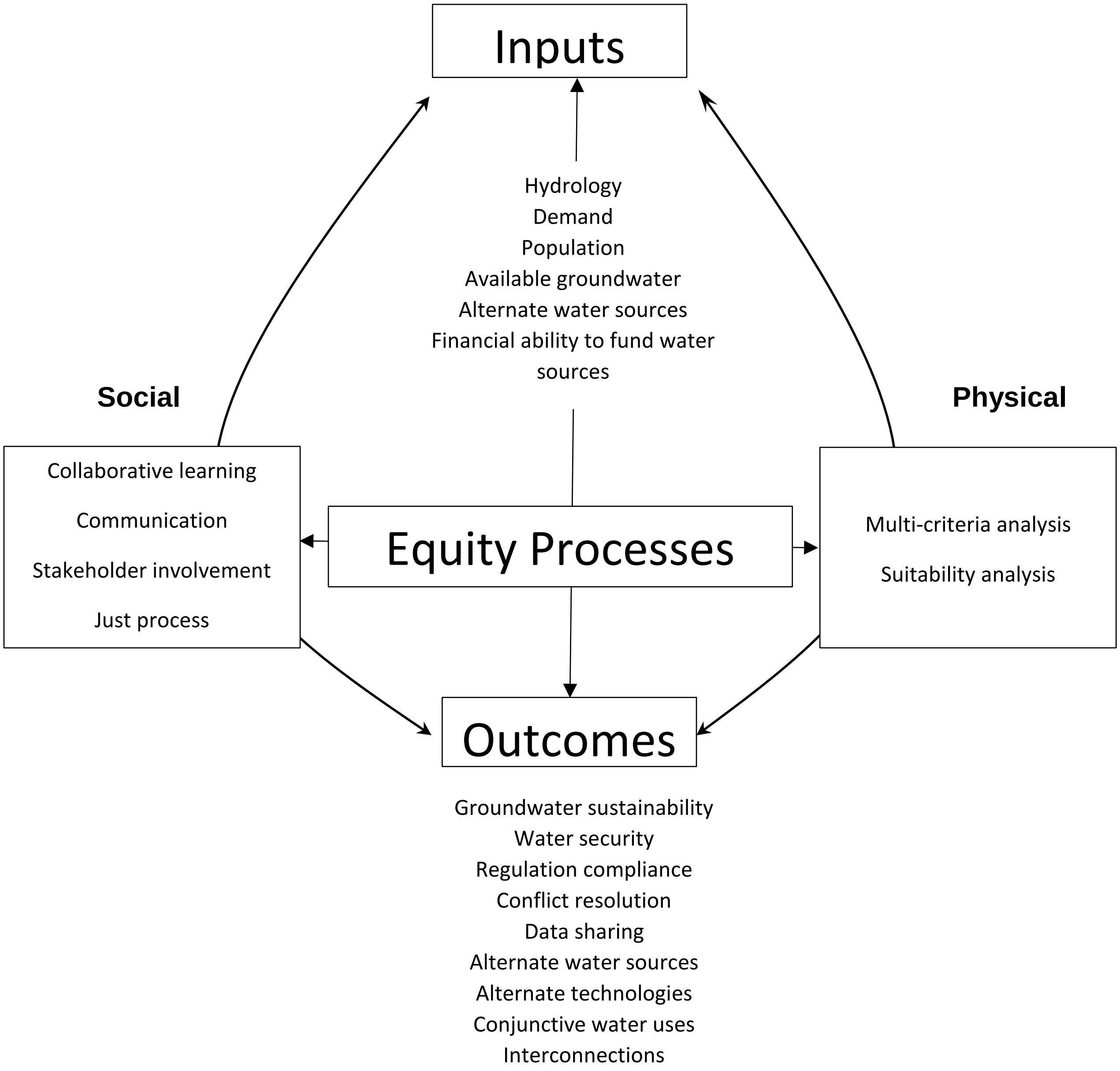

Figure 4. The components of a generalized equitable groundwater management framework (Adapted from Plummer and Fitzgibbon, 2004).

The inputs specific to the groundwater management framework for the CCPCUA are the six criteria discussed in Appendix A and include hydrogeologic characteristics, demand, population, available groundwater, alternate water sources, and the financial ability to fund alternate water sources.

The processes that link input and outcome in this research include equity and multi-criteria analyses (Chapter 5). Suitability maps, collaborative learning, communication, stakeholder involvement, just process, and adaptive management result from the linking processes (Norgaard, 2008; Fisher et al., 2009; Ostrom, 2009; Klein et al., 2014).

For the purpose of this research, desired outcomes distinctive to groundwater management in the CCPCUA include groundwater sustainability and security, regulation compliance, conflict resolution, data sharing, alternate water sources and technologies and alternate water uses, conjunctive water uses and interconnections.

The overarching goal of this research is to explore a multi-criteria, integrated evaluation tool which promotes sustainable aquifer management while equitably developing and reallocating groundwater resources to meet present and future societal needs. As defined in this research, equity and sustainability are integrally linked, as the goal of equity is to protect and manage all impacted by groundwater governance, with an equity framework incorporating the physical and the social considerations. Using the CCPCUA as a case study, the validity of a workable equity framework is tested. Multiple criteria decision analysis and suitability analysis are used to identify areas in the CCPCUA that are physically and socially vulnerable to over-pumping.

3: PROCEDURAL JUSTICE AND THE CREATION OF THE CENTRAL COASTAL PLAIN CAPACITY USE AREA REGULATION

The work conducted in this chapter lead to the publication of an article in a peer reviewed journal article. This chapter therefore represents an earlier version of the published manuscript. Rescuing degrading aquifers in the Central Coastal Plain of North Carolina (USA): Just process, effective groundwater management policy and sustainable aquifers, Water Resources Research https://doi.org/10.1002/2013WR015242.

Key points

- Social-psychological and socio-legal concepts are used to create policy.
- Procedures to develop groundwater management are presented as a template for coastal communities, globally.
- Early stakeholder engagement is vital for successful groundwater management strategies.
- Enforceable and acceptable management strategies result in groundwater recovery and sustainability.

Abstract

Strategic management of degrading coastal aquifers in eastern North Carolina (USA) became imperative after a severe imbalance occurred between withdrawal and recharge rates. To ameliorate this growing problem, an aggressive water policy was developed through public input by creating the Central Coastal Plain Capacity Use Area (CCPCUA) to maintain beneficial use of groundwater resources. Insights from social and organizational psychology, and socio-legal studies are used to evaluate how procedural justice and public participation played major roles to

resolving groundwater resource management problems. A mixed methods approach uses archival data and interviews with various rule-making participants to assess the process of stakeholder involvement that led to creation of the policy. In addition, data analysis techniques are used to evaluate the effects of the policy on aquifer health (through water levels and chloride concentrations) over a ~10-year period. Results suggest that not only did a stakeholder group participate in a process that was deemed fair, understandable, and relatively easy to administer for users and regulators, but public participation resulted in an effective plan that ensures the long-term sustainable use of groundwater. Declining groundwater withdrawals, recovering water levels and decreasing chloride concentrations suggest that the rule is achieving its intended goal of protecting the aquifers from depletion and degradation. This paper touches on global themes that are essential to water demand and consumption, water management techniques and, legislation and water resources protection.

3.1: Introduction

Globally, low rates of groundwater recharge, population growth and high withdrawal rates have severely degraded groundwater (Nelson, 2012). In the Coastal Plain of North Carolina, the Cretaceous aquifers are experiencing declining water levels (as much as 2.4 m per year), large cones of depression, saltwater influx, and low well yields (Giese et al., 1997; Heath and Spruill, 2003; Lautier, 2006). Armed with little more than observational data, in 2002, the State of North Carolina enacted the Central Coastal Plain Capacity Use Area (CCPCUA) rule to protect the negatively impacted aquifers. This regulation was innovative in that social psychological (fairness) and socio-legal (justice) concepts of procedural justice were incorporated into a rulemaking process involving the public. A stakeholder group, was involved in crafting rules related to managing threatened groundwater resources in the State. In this study, the process and the impacts of the process on groundwater management and recovery are evaluated through a mixed methods approach.

The goals of this study are to assess a rule making process and to evaluate the effects of the rule on water resources management and water resource sustainability in the Coastal Plain of North Carolina ten years after inception of the policy. In addition, the process, regulation and subsequent aquifer response can serve as a model for global aquifer management. This is accomplished by (a) exploring how State agencies incorporated social psychological (fairness) and socio-legal (justice) concepts of procedural justice into the rulemaking process (Lind and Tyler, 1988; Greenburg and Colquitt, 2005), (b) assessing groundwater management policy, and (c) analyzing groundwater availability pursuant to enactment of the CCPCUA. To the authors' knowledge, the application of social psychological and socio-legal concepts, as applied to management and sustainability of groundwater is not documented in the literature. The integrated approach uses techniques from the natural and social sciences to meld a variety of viewpoints that explore sustainability science (Mooney et al., 2013; Shaman et al., 2013). The approach is used to (1) review the development of the CCPCUA rule and evaluate the fairness of the rulemaking process to stakeholders, (2) assess the implementation of the groundwater management policy developed through the CCPCUA process, and (3) evaluate the effects of the rule on groundwater sustainability (water levels, groundwater withdrawals, and chloride concentrations). These three goals rarely receive an integrated inspection, as the impacts of the process on the resource occur slowly (Carr et al., 2012). A well-established monitoring system, resulting, in part, from the CCPCUA regulation, gives the study the benefit of long records and high sampling frequency. As a result, this study has the advantage of substantial elapsed time and data to allow an assessment of the association between the rule making process and the outcomes (i.e., management policy and sustainable use of aquifers). Results from this study have global implications for resource managers and technical advisors who are interested in incorporating stakeholders of diverse backgrounds and knowledge into any participatory process that involves the management of any resource.

3.1.2: Socio-political setting

The 15 counties that make up the CCPCUA in the Coastal Plain of North Carolina (Figure 5) are predominantly located in rural areas. Between 1970 and 1990, the total population in these counties increased by 20% from 695,598 to 834,718 inhabitants (http://www.census.gov).

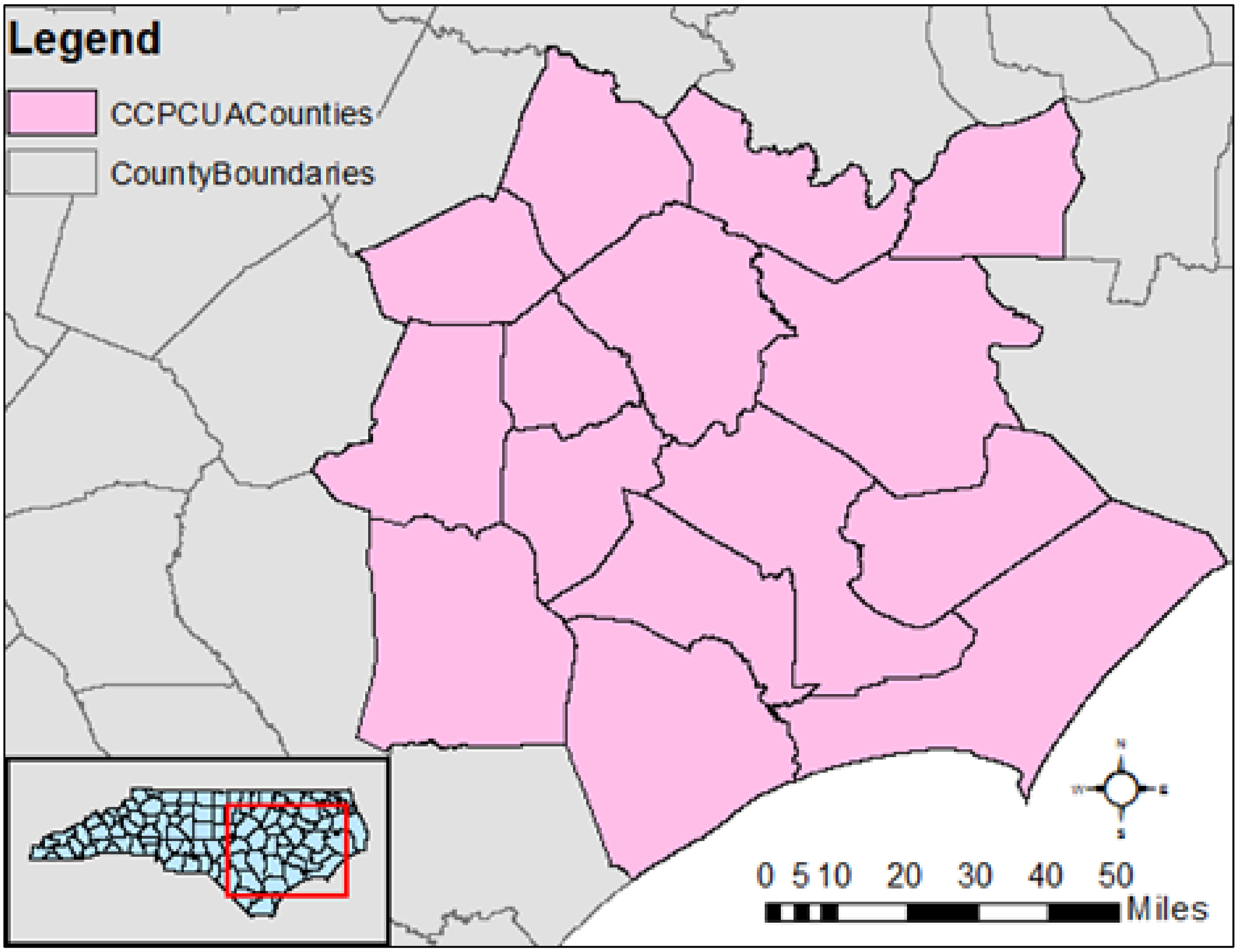

Figure 5. Location of the Central Coastal Plain Capacity Use Area in Eastern North Carolina.

This led to an increase in water demand and, consequently, groundwater withdrawals that threatened the sustainability of groundwater resources in the region, grew (Spruill and Heath, 2003). Groundwater levels in the Cretaceous aquifers declined at unsustainable rates (Appendix C) causing a need for aggressive strategies to manage the threatened aquifers. The 2002 regulation was not the first time the State intervened to protect the aquifers of eastern North Carolina. The Water Use Act of 1967 (http://www.ncwater.org) empowered the State environmental regulatory agency (hereafter the State agency) to create Capacity Use Areas to monitor and regulate water withdrawals from subsurface aquifers and surface water bodies. The 2002 amendment to the Water Use Act of 1967 delineated a new capacity use area, expanded the issuance of withdrawal permits and registrations, and mandated water use reductions over a sixteen-year period.

3.1.3: Hydrogeological setting

The CCPCUA counties overlie a sequence of eastward dipping and thickening sedimentary units that range in age from the Quaternary to the Cretaceous (Figure 6). Historically, most of these units have provided water of high quality and quantity to the inhabitants of eastern North Carolina. However, heavy reliance on the Eocene (Castle Hayne aquifer) and Cretaceous aquifer systems (primarily the Black Creek and Upper Cape Fear aquifers), poor foresight and mismanagement have threatened these resources (Heath and Spruill, 2003). Figure 7 shows the percentage of groundwater withdrawn from each aquifer in the CCPCUA. The major water demands in North Carolina, and the CCPCUA are for public water supply and mine dewatering, with lesser volumes for agricultural, industrial and recreational uses (Figure 8).

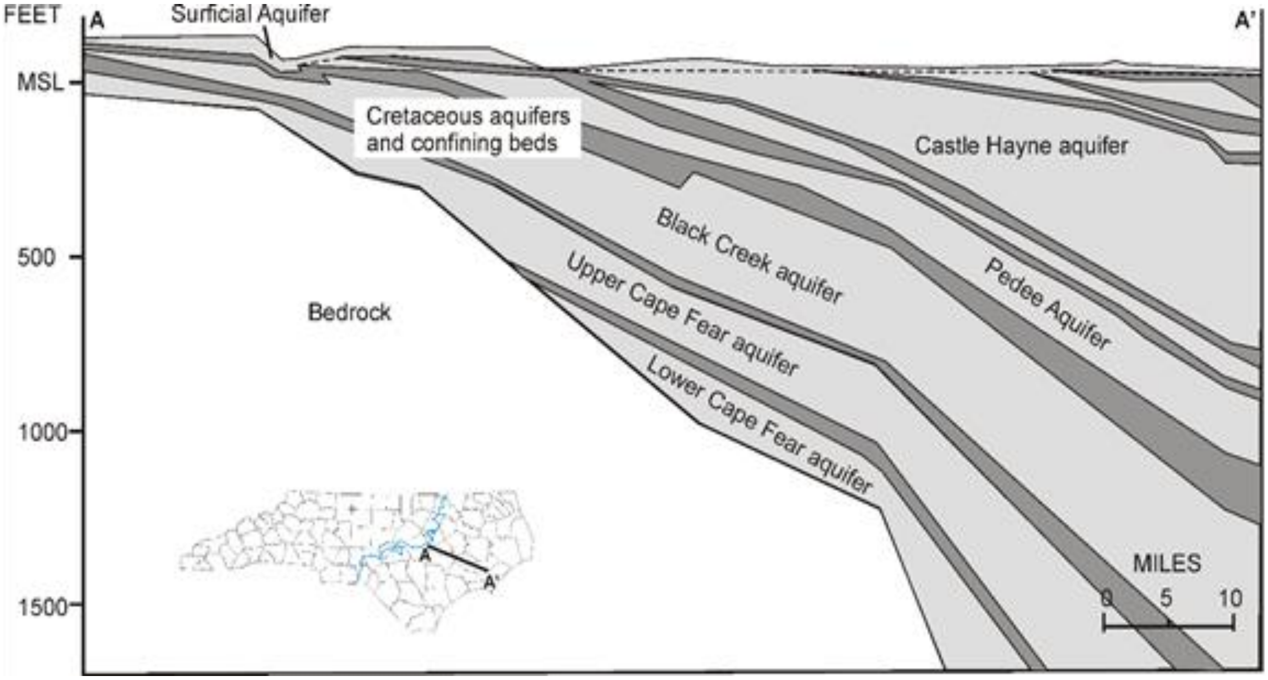

Figure 6. West-East structural cross-section, after Geise et al., 1997.

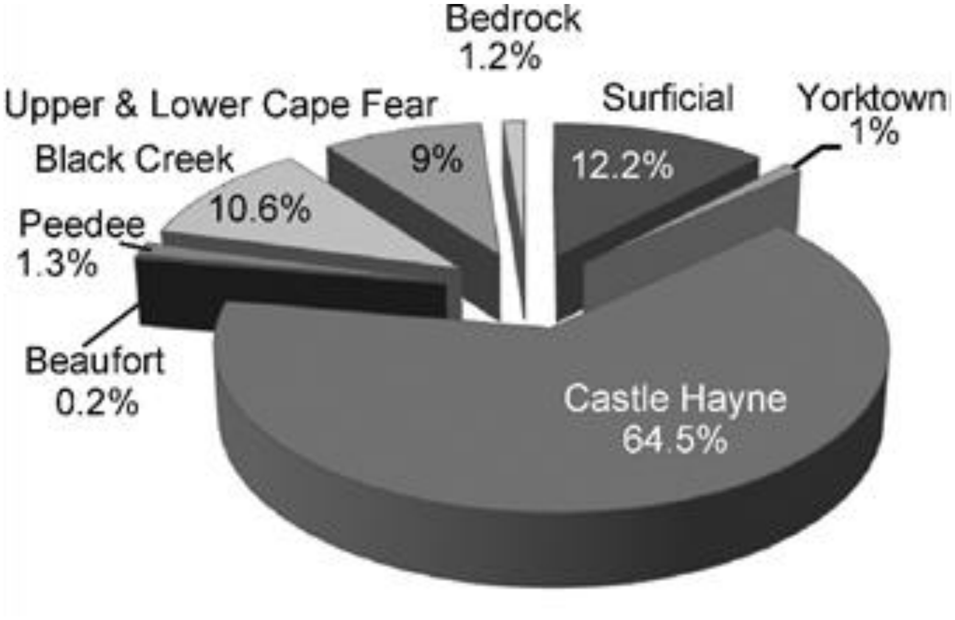

Figure 7. Percentage of total groundwater withdrawal by aquifer in the CCPUA for 2011.

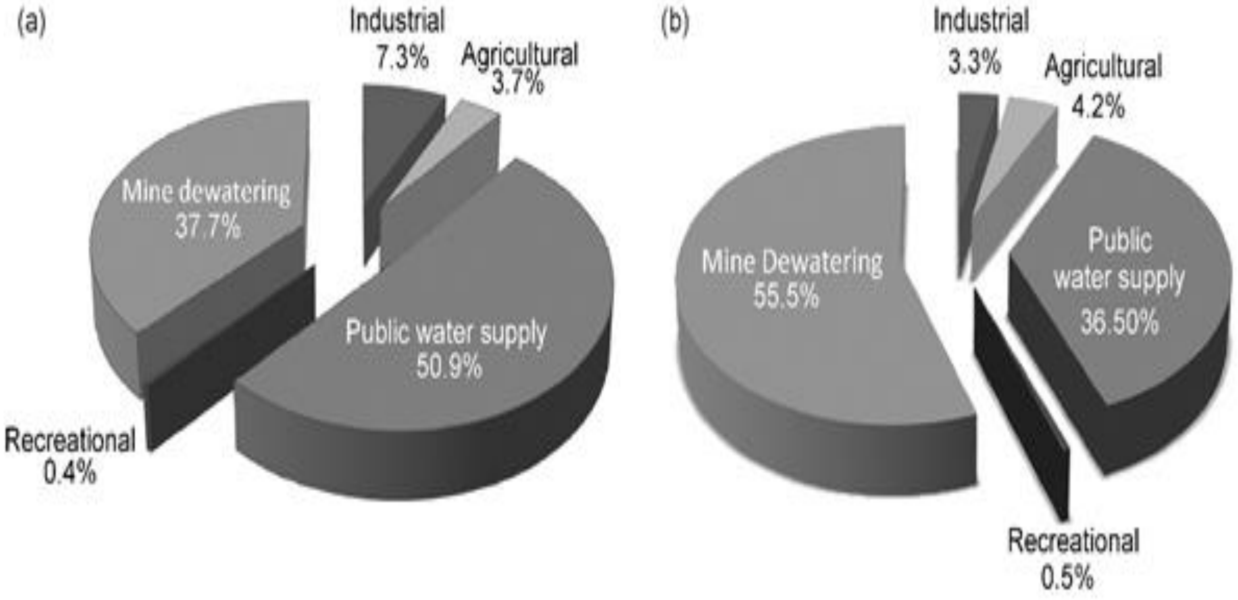

Figure 8. Percentage of total groundwater withdrawal in 2011 by sector in (a) North Carolina and (b) the CCPCUA.

3.1.4: Procedural justice

Procedural justice is a mechanism that is based on perceived fairness of a process (Thibaut and Walker, 1975; Leventhal, 1976, 1980; Straus, 1999; Margerum, 2011). Integral to this mechanism is the involvement in and the acceptance of the process by those impacted by the outcomes of the process. Thus, a positive perception of fairness is frequently viewed as important as the actual outcome (Borsuk et al., 2001; Brockner and Wiesenfeld, 2005; Muller and Kals, 2007). Because outcome and procedure judgments are based on participant treatment, social contracts are usually acceptable when there is full participation in the decision-making process (Lind, 1995; Rohl and Machura, 1997; Deutsch, 2000). Unless those involved in the decision-making process feel heard, with their needs, concerns and questions addressed, compliance and enforcement of any regulation that results from the process may prove difficult. In such cases, participants equate voice, inclusion and respect to fair treatment, process and outcome (Muller and Kals, 2007).

3.2: Methods

A mixed-methods, inductive approach is used to analyze personal interviews, archival data, groundwater levels and chloride concentrations from groundwater wells in the CCPCUA. The approach combines qualitative and quantitative methods to analyze diverse data and eliminate bias that may be inherent in a single data analysis technique (Denzin and Lincoln, 2013). The incorporation of qualitative and quantitative data increases confidence in the validity of the conclusions derived from this study. A generalized approach to the Procedural Justice research is shown on Figure 9. The broad themes that are elucidated from empirical discourse analyses include (a) fairness as perceived by groups as opposed to individuals, (b) fairness defined by self-interests, (c) perspective changes through education, (d) creation and implementation of groundwater management policy, and (e) sustainability of groundwater resources in response to development of collective goals.

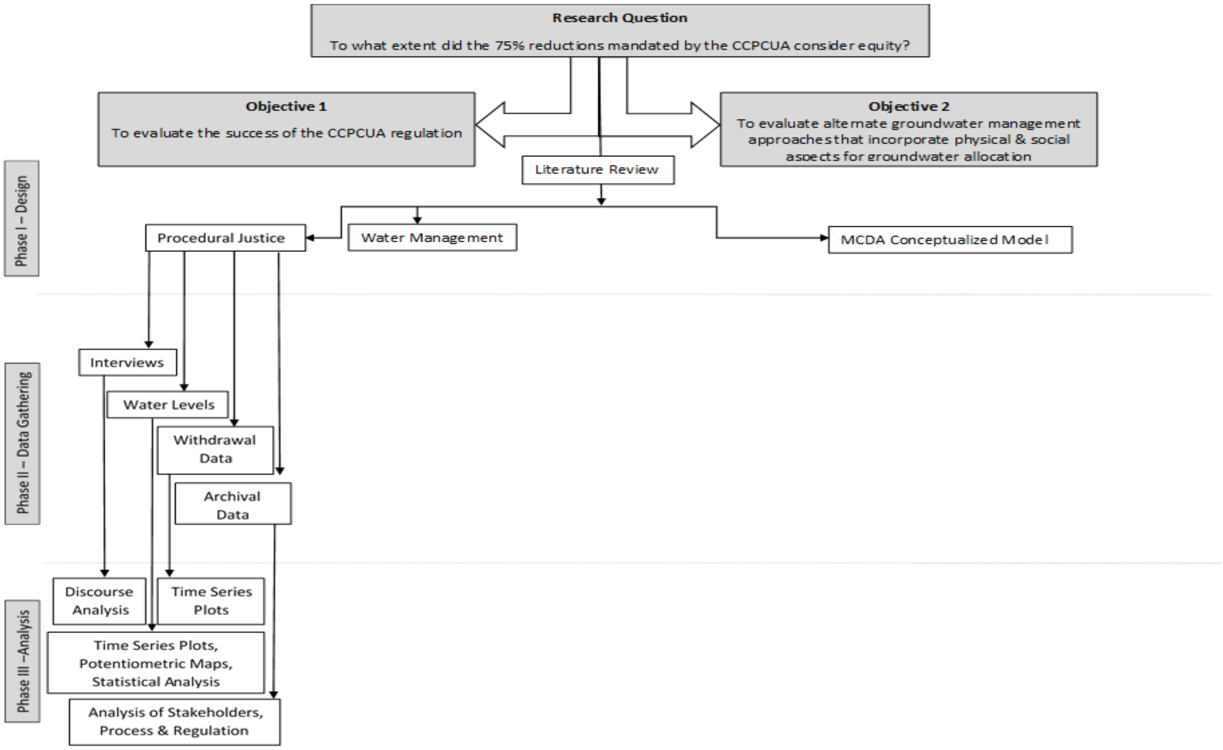

Figure 9. Protocol for the procedural justice research.

3.2.1: Interview process

Personal interviews with participants from many of the representative sectors including State agencies, water utility companies and associations, mining firms, aquaculture and agricultural industries, environmental organizations, and private technical resource advisors were conducted (n = 12) (Table 1).

Participant	n
Municipal/Residential	9
Commercial/Industry	8
Agriculture	4
Environmental	4
Resource Advisors	5
Government	2

Table 1. Participants involved in rule making process

In addition, interviews with individuals from other entities (e.g. water providers) who were not included in the original stakeholder group were used to determine how their perception of the initial process, resultant effects on water quantity and impacts of the process on their business strategies varied from those of the participants. The interviews, which lasted from approximately one hour to six hours, were documented with handwritten notations. Open-ended, semi-structured questions explored professional affiliations, timing and level of involvement, history of the process, alternate solutions, important issues, and individuals' impressions of the need for regulation. An examination of the interviewee's perceptions of justice, consensus impediments, uncertainties, equity and potential consequences for regulation enactment or non-enactment was conducted. Other issues focused on how the CCPCUA fit into an integrated water resources management concept, including who should make policy. The interviewees were chosen using a convenience sampling approach, because the interviews occurred ten years after the CCPCUA committee meetings. Each interviewee was selected based on the availability of their records, notes and recollections.

3.2.2: Archival data

Archival data were obtained from public records, documentation of public hearings, and comments and correspondence submitted to the environmental State agency (i.e. the Department of Environment and Natural Resources). A copy of the original draft rule and a summary of water use regulations in other eastern seaboard states were obtained to compare with the final CCPCUA regulation. Two participants and a facilitator shared their meeting minutes and notes. The meeting minutes outline the issues and important negotiation points. The minutes review those in attendance, the agenda, questions, concerns, discussions and deliberations, handouts and data presentations, reports from outside agencies, actions undertaken, rule reviews, and language changes. Through analysis of meeting minutes, perceptions and changes in perceptions of the water resource problem, rulemaking process, consequences of regulations and workable solutions were determined. The minutes also elucidate how the advisors communicated the technical and hydrogeological issues to the stakeholders.

The meeting notes highlight the critical issues for the committee, as a whole and for individuals representing diverse groups. Through empirical discourse analysis, broad themes are highlighted through the inspection of specific words and language use (Hodges, et al., 2008). Empirical discourse analyses of the notes give insight to the emotional responses of the participants. The notes express emotional sentiments, which are useful for understanding the meeting protocol, the level of respect given to the stakeholders and the development of trust within the group. Included with the meeting notes were letters to the committee from end-users not included in the rulemaking process. The notes and letters were vital to extracting emotional responses of the stakeholders. Keywords and phrases inferred visceral reactions to individual's perceptions of the process and fairness. Copies of the stakeholder resource notebook, and the group charter were obtained from a participant. The charter outlines the goals, expectations, representation and responsibilities of all participants, purpose of the committee, ground rules of the meetings, the decision-making processes and the anticipated final product. These archival data provide context for the interviews and issues of water resources management by yielding insight into how the perceptions of the stakeholders evolved with time.

3.2.3: Groundwater levels

Two sets of groundwater level data were acquired from the North Carolina Division of Water Resources, time series data and potentiometric surface maps ((NCDWR) (http://www.ncwater.org/Data_and_Modeling/Ground_Water_Databases/wellaccess.php). The time series data were acquired from 12 wells drilled into the Black Creek (n = 4) and Upper Cape Fear (n = 8) aquifers in the CCPCUA. These wells were selected because they are located in several counties (n = 5) in the CCPCUA, have sufficiently long records (at least 10-years), and the sampling frequency was generally high (the sampling interval was at least on a monthly basis). The Mann-Whitney non-parametric statistical test was then used to test the null hypothesis of equality of median groundwater levels from 2012 and the year with the lowest annual water levels at the 0.05 significance level. Additionally, the median annual water level in 2012 was compared to the elevation of the top of the respective aquifer to determine whether water levels were merely declining in the aquifer, or if the aquifer was also being dewatered. The second set of data, which consisted of water level maps (i.e. potentiometric surface maps) for the Cretaceous aquifers, was used to assess the extent of the cones of depression in 2005 and 2011 in the CCPCUA. The potentiometric surface maps reflect yearly averages of water levels recorded in wells drilled in each aquifer.

3.2.4: Groundwater withdrawals

Groundwater withdrawal data were also acquired from the NCDWR portal (http://www.ncwater.org/Water_Withdrawals/ResultsTabJS.php?tab=dataandwsrc=gw) to assess the success of the CCPCUA regulation in limiting groundwater withdrawals in the CCPCUA. Time series plots of withdrawal data from each county were first created before the average amount of groundwater withdrawn from each Cretaceous aquifer in 2011 was computed and compared to (a) an established cap of how much water can be withdrawn from each aquifer, and (b) permitted withdrawals in the year 2018.

3.2.5: Groundwater chloride concentrations

Chloride concentrations from 17 groundwater wells in the Black Creek (n = 9) and Upper Cape Fear (n = 8) aquifers were acquired from the same portal as the groundwater level data described above (section 3.2.3). However, unlike the groundwater level data, the chloride data were sampled at a lower frequency than the water level data (each well had less than 10 chloride measurements over each period of record). Thus, rather than using the Mann-Whitney test to assess whether there is any difference through time of chloride concentrations, the highest concentration at any point in the record of each well was compared to the most recent 2012 chloride concentrations.

3.3: Mechanics of process

Initial attempts to formulate groundwater management regulations by the State environmental agency, without outside input, were met with opposition. Although the initial regulation was based on scientific input, many attendees at early public meetings expressed apprehension that the State agency was biased, out of touch with the demands of the users and did not have sufficient authority to enforce the regulation (Smutko, personal communication, 2010). Because of these objections, the State agency opted to change course by involving stakeholder representatives to formulate policy thereby relegating the role of the agency to that of open-minded convener. The State initiated a mechanism to develop strategies to manage groundwater in the Coastal Plain that comprised selection of participants (facilitators, stakeholders, and resource advisors), setting protocol for meetings, and crafting regulation.

3.3.1: Roles of facilitators

The State agency chose independent agents to facilitate the CCPCUA rule making process because it is the responsibility of the facilitator to create a cohesive group out of a disparate and diverse assembly to address problems, while maintaining an equal commitment to all perspectives (Poirier Elliott, 1999; Kray et al., 2005). Although the facilitators took part in the process, they did not have a stake in the outcome. The roles of the facilitators were two-fold. First, the facilitators had to determine and evaluate issues, craft a protocol for choosing stakeholders, ascertain the availability of pertinent data, and make recommendations for how to proceed with the process. The second role consisted of facilitating the rule-making process by moderating exchanges between the various stakeholders (Lind and Tyler, 1988). The facilitator's broad goals were to give the conveners some distance from the rulemaking process and guide the process and participants to a mutually agreed upon consensus (Poirier Elliott, 1999).

The facilitators created the CCPCUA stakeholder committee from referrals, suggestions made by the State agency, and written comments submitted during public meetings. Follow-up interviews with prospective committee members focused on probable contentious issues and factors that would hinder the construction of a group willing to work together to create a usable set of regulations. The facilitators wanted to keep the group only as large as they deemed efficient and representative, i.e. a group of minimum size and maximum representation (Smutko, personal communication, 2010).

3.3.2: Roles of stakeholders

The stakeholder committee members that were chosen to represent diverse stakeholder interests included agents from municipal, residential, commercial, industrial, agricultural and environmental sectors in the Central Coastal Plain (Table 1). For clarity and simplicity, the interested parties that were members of the stakeholder committee are hereinafter referred to as ‘stakeholder representatives’, whereas the interested parties that were not members of the committee are referred to as ‘stakeholders’ or ‘broader stakeholder group’. The purpose of the committee, as stated in the Committee Group Charter, was to “…determine the rules governing permitting and water allocation, and the principles on which the rules will be based. The intended outcome will be a mutually acceptable water use permitting rule under the Water Use Act that ensures fairness and predictability to water users and protects the long-range productivity of surface and groundwater.” Therefore, the role of the stakeholder representatives was to add their input to the rule-making process and keep their respective constituents informed.

3.3.3: Roles of resource advisors

In addition to the convener, stakeholder committee and facilitators, five resource advisors took part in the rule-making process. The advisors included technical consultants and scientists from private firms, a science based federal agency, academia, and environmental State agency (Table 1). These resource advisors presented the background of the problem, including the hydrogeologic setting, estimates for safe well yields and consequences to the aquifers if the status quo was maintained. The role of the technical advisors was to assist the stakeholder representatives in understanding the technically complex information, which was often outside of the representatives' experiences. The resource advisors played a critical role in the CCPCUA process; however, they had no power as decision makers.

3.3.4: Protocol and CCPUA final rule

The first meetings to draft the CCPCUA rule addressed the purpose and scope of the committee, the guidelines for a consensus process, a background of the problem, and discussions of the issues and the committee charter. Subsequent meetings focused on actual rule making. The conveners set a demanding timetable for the stakeholder representatives group which met weekly over a two-month period. Yet, the group was able to come to consensus on regulatory and measurement parameters, the establishment of a base year and base rates, allocation goals, monitoring, and reporting procedures. Specifically, the rule requires registration and reporting for groundwater users withdrawing between 38 and 379 m^3 (10,000 and 100,000 gallons) per day within the 15 county area. Surface water withdrawals above 38 m^3 (10,000 gallons per day) require registration and annual reporting. Groundwater withdrawals from the Cretaceous aquifers of more than 379 m^3 (100,000 gallons) per day require permitting. In this context, 'registration and reporting' means informing the state about withdrawal volumes, whereas 'permitting' means getting permission from the state before withdrawal can occur.

This contingent agreement, which is an agreement based on the results of a future scenario (Dictionary of Conflict Resolution, 2002), involves making graduated reductions in groundwater withdrawals over a 16-year period (Figure 10). The reductions, of up to 75%, set a daily withdrawal rate that is based on approved base rates (ABR). The reductions are based on the severity of the aquifer conditions at various locations within the CCPCUA. However, the rule has a built-in flexibility that allows the water users to negotiate with the State agency on mutually agreeable base rates.

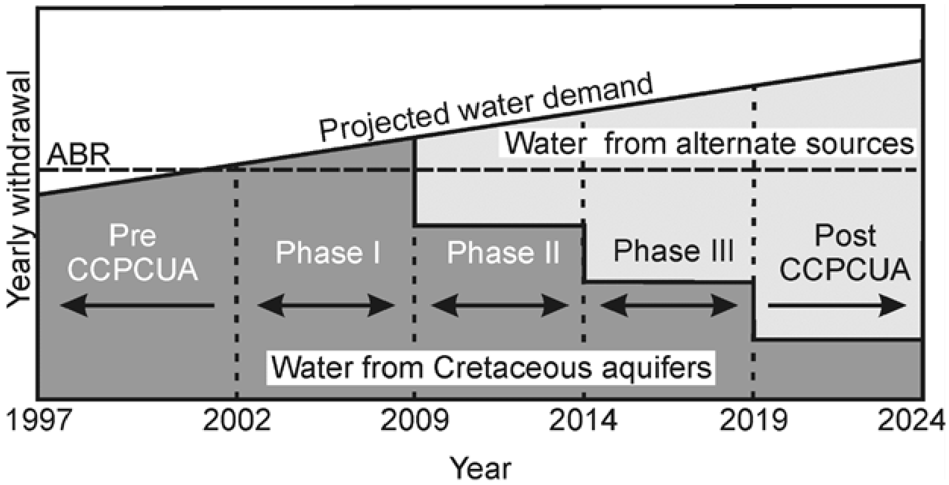

Figure 10. Schematic summarizing the timeline for reducing groundwater withdrawals after CCPCUA was enacted (Modified from http://www.ncwater.org/Permits_and_Registration/Capacity_Use/Central_Coastal_Plain/CCPCUA_rule_summary_FAQ.php).

Regions experiencing saltwater encroachment, dewatering and declining water levels are subject to different levels of withdrawal reductions. These reductions were set to occur in three phases over the 16-year period, with re-evaluation by the state agency at the end of each phase. Each withdrawal reduction is as little as 10% in areas of declining, but non-threatened water levels, and up to a maximum of 25% in areas of saltwater intrusion. The reductions specific to each municipality were determined by the agency based on reports of daily water withdrawals, water levels and salinity. Each permit holder was required to develop water conservation plans and strategies for reducing groundwater withdrawals.

3.4: Evolution of process

3.4.1: Stakeholder engagement

The development of the CCPCUA suffered from errors and mis-directions, before creative solutions were proposed to achieve eventual consensus about differing views concerning groundwater management in eastern North Carolina. Early errors that were committed by the State included not involving stakeholder representatives in the initial rule making process. As a result of this omission, the initial proposal from the State agency was not well received by the broader stakeholder group as it left them feeling disempowered and distrustful of the intentions of the State (John Morris, personal communication, 2010). The draft regulation was therefore not only unpopular, and largely unsupported, but would also have been extremely difficult to enforce (Nat Wilson, personal communication, 2012). Previous research has shown that exclusion of stakeholder representatives from decision making processes typically perpetuates an unwillingness to comply with rules proposed by regulatory agencies (e.g., Brockner and Wiesenfeld, 2005).

Although the State held informational meetings to inform the public about their intentions, some observers viewed these events as forums with a mechanism for limited feedback from municipalities and stakeholder groups (Smutko, personal communication, 2010). There was little question, however, that the long term, continued use of the aquifers was threatened and that allowing the situation to continue unmanaged, was an option that would not benefit anyone. It was not until those with the power to enact and enforce regulations (i.e. the State agencies) gave voice to those impacted by the regulations (i.e. the stakeholder groups) that a different direction was taken to find creative solutions that were amenable to all stakeholder groups. This step involved changing the approach by allowing a third party to facilitate the rule making process. In the revised approach, the State agency could not act as an impartial convener, as it is their mandated role to advise the State with information about and remedies to groundwater problems. Therefore, the role of the convener was that of major driver or catalytic agent; one that sped a change process, yet retained its original function (Morse, 2010).

In contrast to the initial approach undertaken by the State, the facilitators involved representatives from diverse stakeholder groups (i.e. the stakeholder committee) at the beginning of the process so that they could collaborate in crafting the CCPCUA rule. The members of the stakeholder committee came to the first meetings with diverse agendas and fears of having untenable regulations thrust upon them. Consequently, the facilitators had to allay the concerns of the stakeholder representatives by facilitating a mechanism that allowed for the redrafting of the initial regulations that were developed by the State. The addition of a resource advisor to the process also helped to convince the stakeholder representatives that the State agency was willing to play the role of convener in the process. Only after this was done did the stakeholder committee begin to work collectively to achieve a common goal (Smutko, personal communication, 2010).

3.4.2: Perception of process

As demonstrated in archival data, a shift occurred in the perceptions of the stakeholder representatives, how the representatives responded to each other, and in the way that the rule making process evolved over time. The data reveal that at the onset of the process the stakeholder representatives felt that the individual groups that they represented would be unfairly treated by any proposed legislation. Language used to communicate displeasure included words and phrases like “Byzantine”, “too expedient”, “punishes all”, “less equipped”, “suffer”, “hard to explain”, “innocent victims” etc. (Boyette, personal correspondence, 4/6/2000; Loomis, personal correspondence 4/4/2000). Furthermore, some groups thought that they contributed to the wellbeing rather than degradation of the aquifers (e.g. farmers contributed to aquifer recharge by maintaining pervious surfaces), whereas other groups felt the rule gave unequal treatment to other water users (e.g. mining operators were allowed to dewater aquifers whereas other entities were not) (Boyette, personal correspondence, 4/4/2000). Owing to the deliberations during the committee meetings that allowed for different viewpoints from each stakeholder representative to be addressed, these perceptions quickly began to change. This transition was due, in part, to presentations made by the resource advisors in non-technical language. Previous researchers have found that advisor input is usually beneficial to help less technically inclined stakeholder representatives understand the limitations of data, as well as inform them as to the usefulness of various proposed strategies (Maguire, 2003). Furnished with the scientific justification for the regulation, the committee members grasped the magnitude of the problem and became more open to other people's ideas, had greater trust in their colleagues, and their understanding of the need for regulation increased. Personal notes with phrases such as "good pitch", "good reaction", "tone of participants not hostile", and "not too many people participate, but resistance isn't expressed!" (Bierly, personal meeting notes, 2/21/2000) reveal the atmosphere of growing acceptance in the later meetings.

Educating the stakeholder representatives began a paradigm shift to accepting the need for a workable and creative regulatory solution. Tasked with the authority to represent their constituents, each stakeholder representative originally voiced specific needs and demands, and came to the process representing positions that benefited their short term, self-interests. As the stakeholder representatives became educated about the issues, the focus shifted from the individual objective to the collective goal. At the beginning of the process, the way that the stakeholder representatives perceived fairness of the process was more important when they acted as individuals, rather than as a group (Leung et al., 2007). Initially, each stakeholder representative was less concerned about the impacts of regulations on other stakeholders than themselves. On the short term, the self-interests of the individual stakeholders encouraged a desire to belong and encouraged discussions of perceived issues of fairness (Gillespie and Greenberg, 2005). Identifying and communicating conflicts ultimately promoted collaboration and cooperation within the stakeholder committee.

As the meetings progressed, the committee not only decided that regulation was needed, but they also acquired a collective perspective that shifted their focus from the individual to the group. By coming together to craft a regulation that met the needs of the stakeholder representatives and those of their cohorts while maintaining aquifer health, the representatives felt a measure of power through their representation in the proceedings (Lind and Tyler, 1988; Carr et al., 2012). Comments such as “we learned, discussed, compromised and developed some proposed rules to deal with a serious challenge to our region’s well-being as well as health of the citizens” (Bierly, personal communication, 10/8/2000) indicate that the stakeholder representatives were frequently able to see beyond their individual needs to work cooperatively toward the betterment of the larger system (Ostrom et al., 1999). As the perceptions of the stakeholder representatives evolved, the representatives came to agree on a common view of the benefits of regulation because they had grown to be more trustful of the process.

3.4.3: Policy development

Owing to different demands for groundwater resources (Figure 8), a contingent settlement that validated each stakeholder representative’s concerns and viewpoints was accepted as a final solution. Originally, the state agency proposed individual evaluations of each groundwater withdrawal permit, with the agency assigning remedial requirements on a case-by-case basis. This left the stakeholder representatives uneasy about their loss of control and lack of a mechanism for predicting future changes that would impact their businesses (Smutko, personal communication, 2010). Thus, the stakeholder representatives elected to take a different approach to solving the water management problem by crafting a schedule of tiered reductions which provided end users with a timeline for projecting reductions of groundwater withdrawals (Figure 10). Surprisingly, the stakeholder representatives eventually agreed on a wider ranging remedy than that originally proposed by the State agency. The representatives concluded that the concept of permitting addressed many of their concerns, including the prevention of dewatering or salt-water intrusion. The establishment of "critical areas" which delineated the regions of greatest stress allowed for the most stringent regulations within those areas, whereas defined timetables with specific reduction objectives gave users clear goals and targets for planning purposes as well as an incentive to enact conservative measures. The results suggest that had the regulation not included contingencies with clearly outlined objective measures and incentives that gave the stakeholder representatives a measure of predictability, the regulation would not have been supported. The permitting and registration process, contingent on withdrawal volumes, allowed the state agency to actively monitor and assess the aquifers.

3.4.5: Perceptions of fairness

The inclusion of three independent groups in the CCPCUA process meant that from the onset, there were different perceptions of fairness because each group entered the rule-making process with a different concept of what constituted a fair process. Although the idea of fairness in the public arena is the mutual acceptance of shared values and principles for the improvement and distribution of common goods (Syme and Nancarrow, 1997; Rawls, 1999), the stakeholder representatives mostly viewed fairness from a financial perspective. The representatives usually countered solutions, suggested by others, with responses based on economic impacts to their ventures (e.g., farmers do not have the finances for monitoring water withdrawals). From the perspective of the facilitator, the outcome (i.e. the final regulation) was irrelevant and thus, fairness only applied to the process, not the resource. Whereas the facilitators were interested in protecting the process, the conveners focused on protecting the aquifers. Eventually, because each group contributed unique, yet mutually beneficial skills and needs to the process, a common language emerged that allowed the conveners, stakeholder representatives and facilitators to reach a mutually accepted idea of fairness. A fair process with a broad base of stakeholder representation combined with public participation often leads to regulations that are generally supported and easily enforced (Margerum, 2011).

Although other studies have documented less successful stakeholder processes (e.g., Maguire and Lind, 2003), such shortcomings have in part, been a consequence of participant groups (e.g. State agencies) assuming numerous capacities in the process. In the case of the development of the CCPCUA, each player had a different and distinct role and as a result, the stakeholder representatives perceived the different groups or individuals who acted as conveners, facilitators, and resource advisors, as impartial. (However as stated above, the convener could not be entirely impartial.)

The role that the facilitators played in directing the process also contributed to how fair the stakeholder representatives perceived the process. For example, the facilitators recommended that the stakeholder committee begin developing regulation based on two different draft regulations: one regulation drafted by the State agency, and another regulation drafted by a resource advisor. The facilitators focused the group thought process by having them respond to a set of questions: (1) What do you like about either plan? (2) What do you not like about either plan? (3) What is missing from either plan? This approach gave respect and voice to all the members of the stakeholder committee. And as a result, many stakeholder representatives perceived the process be fair because they were given a fair opportunity to discuss issues as well as ask and answer questions that pertained to the issues affecting their constituents.

Typically, procedures are deemed just when those affected by the outcome find the outcome acceptable (Lind, 1995; Rohl and Machura, 1997; Deutsch, 2000; Borsuk et al., 2001; Brockner and Wiesenfeld, 2005; Muller and Kals, 2007). However, in the case of the development of the CCPCUA, involvement in the process appeared to play as important a role in the perception of fairness as the final outcome. The stakeholder representatives and regulatory bodies deemed the regulations fair and successful because the regulations provided for input and predictability to the stakeholder groups and accomplished the ultimate goal of putting into place a set of rules that managed threatened aquifers, halted accelerating depletion of groundwater and set into action conservation measures. The regulations were not only acceptable to the stakeholder representatives, but enforceable by the State environmental agency. In contrast, those groups that were not involved with the actual process were unhappy with the outcome and therefore viewed it as unfair. Interestingly, some of the parties that expressed dissatisfaction with the outcome were stakeholder groups that had representatives on the stakeholder committee.

3.5: Impact of rules

3.5.1: Groundwater management policy

An economic implication of the CCPCUA is that the rule has encouraged alternate sources of water and conjunctive water use to reduce the reliance of Coastal Plain communities on Cretaceous aquifers. Thus, municipalities in the Central Coastal Plain have invested greater than $340 million in new surface water treatment plants, new groundwater well fields, and other technologies to temporarily store water from surface and subsurface sources in deep aquifers (i.e. aquifer storage and recovery). Furthermore, water distributors are developing interconnections and inter-basin transfers to serve as backup systems to prevent threats to cultural and social stability to the region. As a commodity once in great abundance in North Carolina's Coastal Plain, groundwater is now a resource undergoing thoughtful planning. The creation of the CCPCUA forced a comprehensive look at broader management options for groundwater resources, the legacy of which is the long-term investment in sustaining water resources.

Perceptions about water use are changing because of the CCPCUA. Public water suppliers must now comply with conservation measures outlined in the rule. Required water conservation plans include conservation-based rate structures, water loss reduction programs, irrigation conservation proposals, retrofit programs, public education, and water reuse projects. In addition, the rule allows for the sale or transfer of water or sale or transfer of permitted withdrawal rates. Equipped with a more complete knowledge of the underlying conditions, the state and local water systems have better tools with which to plan and manage water. All of these are positive outcomes from the creation of the CCPCUA.

3.5.2: Sustainability of groundwater resources

Assessments of groundwater levels in the Black Creek and Upper Cape Fear aquifers reveal the state of water levels in the Cretaceous aquifers before and after implementation of the CCPCUA phased reductions (Appendix C). Examples of groundwater wells that have sufficiently long-time records from the Cretaceous aquifers show that groundwater levels have recovered by between 1 and 17 m (median annual water levels) in the CCPCUA after implementation of the area rules (Figure 10). The differences between the median annual water levels in the year with the lowest water levels and the median annual water levels in 2012 are shown to be significant ($p < 0.0001$) at the 0.05 significance level. The results also indicate that the tops of the aquifers for the wells are below the 2012 water levels indicating that these aquifers are not being dewatered (Table 2). An example of a well with a long record (Figure 11) showing the magnitude of the decline and rebound in water levels over a >35 year period suggests that the change in slope in the water level record after 2008 is likely consequence of the impacts of the CCPCUA rules on groundwater management policy.

Name	County	Well ID	Aquifer	Latitude	Longitude	Elevation of top of aquifer (m)	Lowest median annual water level (m)	Median annual water level in 2012 (m)	Water level difference (m)	Year of lowest water level	p value
Chicod	Pitt	O 23L3	Upper Cape Fear	35.4636	-77.275	-135.6	-22.88	-17.05	5.83	2008	7.07E-123
Comfort	Jones	U 26J10	Upper Cape Fear	34.9694	-77.503	-219.2	-17.74	-15.82	1.91	2009	1.03E-122
Cove City	Craven	R 23X9	Upper Cape Fear	35.1723	-77.311	-223.1	-40.92	-31.38	9.54	2007	1.69E-84
DH Conley High Sch (a)	Pitt	N 23P2	Upper Cape Fear	35.53	-77.327	-113.4	-20.64	-14.22	6.42	2007	7.08E-123
Moss Hill	Lenoir	R 29T4	Upper Cape Fear	35.1962	-77.753	-92.0	-0.75	3.98	4.74	2002	2.73E-76
North Pitt High School (a)	Pitt	L 24B4	Upper Cape Fear	35.7496	-77.365	-66.1	-7.62	-5.05	2.58	2004	0.000134
Saulston			Upper Cape Fear	35.4698	-77.85	-7.0	-8.48	-2.95	5.53	2005	1.91E-78
Savannah School	Lenoir	P 26U5	Upper Cape Fear	35.3367	-77.512	-110.6	-36.39	-19.71	16.68	2000	1.88E-68
Cove City	Craven	R 23X8	Black Creek	35.1723	-77.311	-132.3	-41.48	-31.79	9.69	2008	1.03E-122
Moss Hill (a)	Lenoir	R 29T7	Black Creek	35.1962	-77.753	-20.7	-0.79	4.31	5.09	2001	1.18E-36
Savannah School	Lenoir	P 26U7	Black Creek	35.3367	-77.512	-52.4	-35.92	-19.32	16.60	2000	7.03E-85
Well Field 258	Onslow	W 25F8	Black Creek	34.8104	-77.487	-132.0	-60.59	-48.89	11.70	2006	4.22E-68

Table 2. Median annual water levels for each well during the year with the lowest median water levels and 2012. Also included are the p values from the Mann-Whitney non-parametric test.

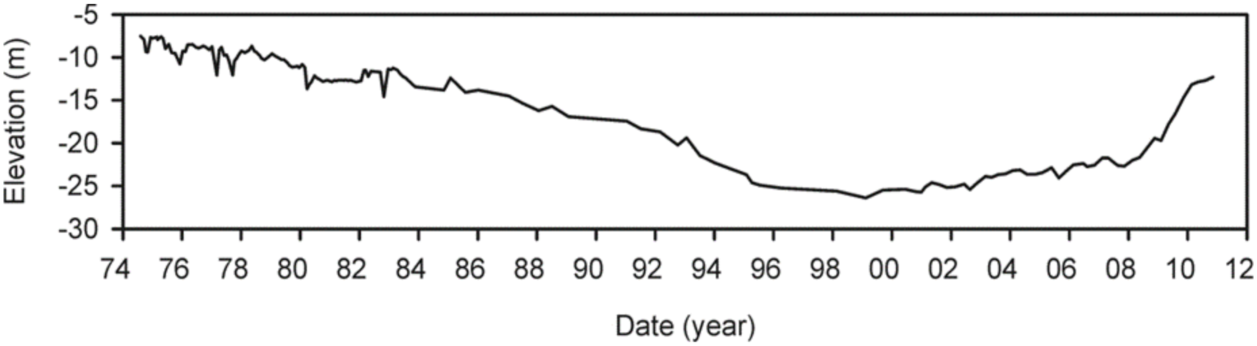

Figure 11. Holistic water levels (1974-2011) from a well drilled into a Cretaceous aquifer showing groundwater levels before and after enactment of the CCPCUA.

Assessments of potentiometric surface maps reveal the state of water levels in the Cretaceous aquifers before and after commencement of the CCPCUA phased reductions in 2002 (Figure 12). The results indicate that the cones of depression in the Cretaceous aquifers have reduced in size over the 2005-2011 time period (Figure 12) illustrating that the CCPCUA phased reductions have contributed to rising water levels in the aquifers and aquifer sustainability.

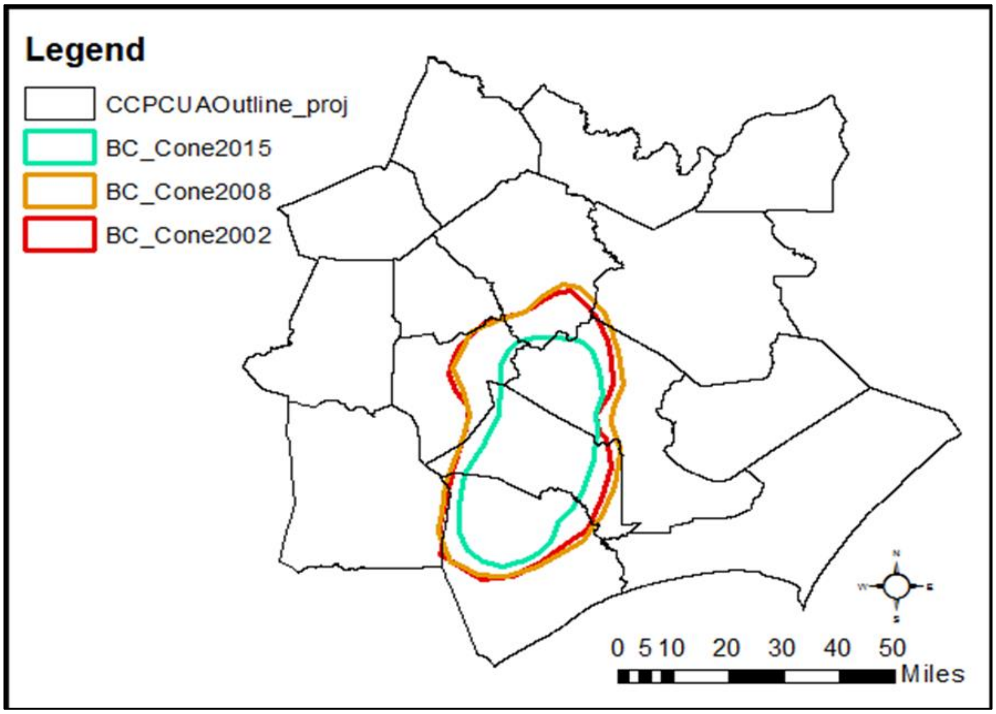

Figure 12. Extent of the cone of depression the Black Creek aquifer in2002, 2008, and 2015. Only the -18m (-60ft) contour for each year is shown for ease of comparison (Data acquired from http://www.ncwater.org/Education_and_Technical_Assistance/Ground_Water/AquiferCharacteristics/matrix.php).

The rebounding water levels are a consequence of reductions in groundwater withdrawals from the Central Coastal Plain after the establishment of the CCPCUA (Figure 13). The reductions in groundwater withdrawals are especially evident in counties with newly developed alternate sources of water (e.g. Lenoir County).

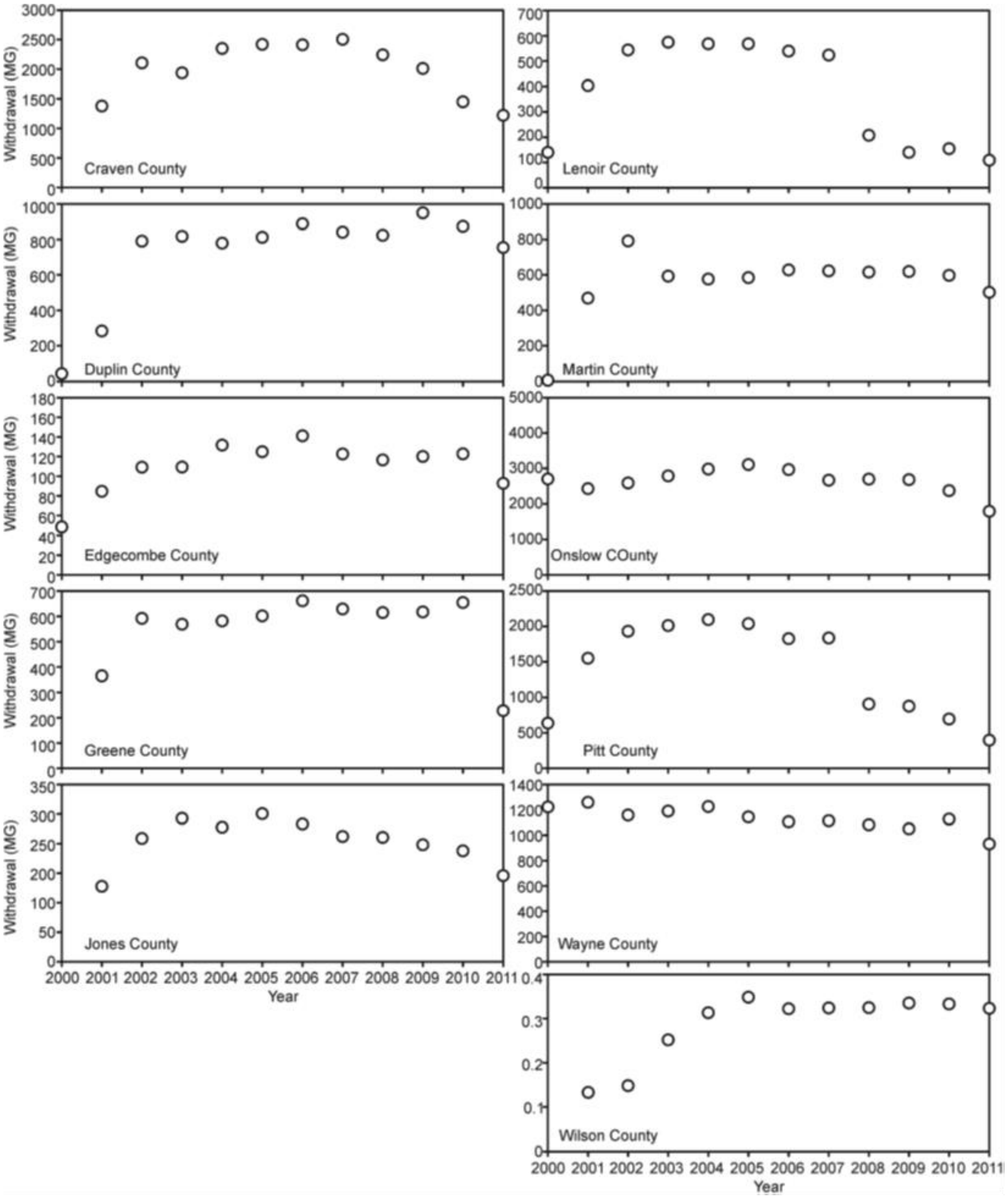

Figure 13. Example of time series showing changes in groundwater withdrawals after enactment of the CCPCUA (MMG= million gallons.

Withdrawal data for each aquifer indicate that withdrawals have declined by >50% of the ABR for most of the aquifers in the CCPCUA and that the water managers and stakeholders are well on their way to meeting the targeted 2018 withdrawal rates (Table 3).

Cretaceous Aquifer	Approved Base Rate (MMLD)	Average 2011 Withdrawals (MMLD)	2018 Permitted Withdrawals (MMLD)
Peedee	15.14	0.87	4.16
Black Creek	99.93	51.10	33.69
Upper Cape Fear	101.45	38.99	36.34
Lower Cape Fear	0.19	0.04	0.19
Total	216.71	91.00	74.38

Table 3. Approved based Rate (ABR), 2011 average groundwater withdrawals and 2018 permitted groundwater withdrawals from each Cretaceous aquifer in the CCPCUA (MMLD= millions liters per day).

Analyses of chloride concentrations indicate that salt levels in the Cretaceous aquifers have decreased by between 7 and 77% from the year with the highest concentrations to 2012 (Table 4). The declining chloride concentrations suggest a reduction in the rate at which saltwater intrusion is occurring in the Black Creek and Upper Cape Fear aquifers. Declining chloride concentrations, in addition to rebounding water levels and declining withdrawals, suggests that the current groundwater management policy is contributing to the long-term sustainability of Cretaceous aquifers in the CCPCUA.

Name	County	Well ID	Aquifer	Latitude	Longitude	Highest chloride level (ppm)	Chloride level in 2012 (ppm)	Chloride level difference (ppm)	Year of highest water level
Lee Creek	Beaufort	P17I9	Black Creek	35.38645	-76.783	11900	6888	5012	2007
Cox Crossroads	Beaufort	P19M4	Black Creek	35.37348	-76.783	5411	1252	4159	2007
Wilmar	Beaufort	P21K5	Black Creek	35.38148	-77.087	593	434	159	2007
Wilmar	Beaufort	P21K9	Black Creek	35.38148	-77.087	239	194	45	2010
Aurora II	Beaufort	Q17D4	Black Creek	35.32609	-76.802	16435	16435	8873	2008
Clarks	Craven	R23X10	Lower Cape Fear	35.1723	-77.311	3677	2224	1453	2006
Clarks	Craven	S22J10	Black Creek	35.13747	-77.171	194	179	15	2004

Table 4. Chloride levels for each well during the year with the highest chloride levels and 2012.

Name	County	Well ID	Aquifer	Latitude	Longitude	Highest chloride level (ppm)	Chloride level in 2012 (ppm)	Chloride level difference (ppm)	Year of highest water level
Clarks	Craven	S22J12	Upper Cape Fear	35.13747	-77.171	2802	1735	1067	2009
Pink Hill	Duplin	T29G10	Lower Cape Fear	35.05632	-77.807	111	42	69	2011
Beaver Creek	Jones	S26I2	Lower Cape Fear	35.13948	-77.53	80	74	6	2007
Jones Middle School	Jones	T24J1	Lower Cape Fear	35.06575	-77.345	5959	3145	2805	2009
Jones Middle School	Jones	T24J7	Upper Cape Fear	35.06575	-77.345	322	245	77	2010
Gold Point	Martin	J22P6	Lower Cape Fear	35.85652	-77.248	906	892	14	2007

Table 5 continued. Chloride levels for each well during the year with the highest chloride levels and 2012.

Name	County	Well ID	Aquifer	Latitude	Longitude	Highest chloride level (ppm)	Chloride level in 2012 (ppm)	Chloride level difference (ppm)	Year of highest water level
Gold Point	Martin	J 22P7	Upper Cape Fear	35.85652	-77.248	437	343	94	2007
Bear Grass School	Martin	K 21R5	Lower Cretaceous	35.7686	-77.129	5808	4784	1024	2007
Bear Grass School	Martin	K21R6	Lower Cape Fear	35.7686	-77.129	4453	2420	2033	2008
Parkertown	Onslow	X 22H6	Black Creek	34.72964	-77.21	9880	4596	5284	2008
Folkstone	Onslow	Y 25Q8	Black Creek	34.61137	-77.482	1849	1062	787	2008
North Pitt High School	Pitt	L24B3	Lower Cape Fear	35.74958	-77.364	961	758	203	2004

Table 6 continued. Chloride levels for each well during the year with the highest chloride levels and 2012.

Name	County	Well ID	Aquifer	Latitude	Longitude	Highest chloride level (ppm)	Chloride level in 2012 (ppm)	Chloride level difference (ppm)	Year of highest water level
North Pitt High School	Pitt	L24B4	Upper Cape Fear	35.74958	-77.364	1000	284	716	2007
North Pitt High School	Pitt	L24B5	Upper Cape Fear	35.74958	-77.364	400	327	12	2010
Falkland	Pitt	L25P1	Lower Cape Fear	35.69466	-77.49	239	227	12	2010
West Research Campus	Pitt	M 25F5	Upper Cape Fear	35.63956	-77.483	67	57	10	2006
D H Conley High School	Pitt	N23P4	Upper Cape Fear	35.52996	-77.326	73	65	8	2007

Table 7 continued. Chloride levels for each well during the year with the highest chloride levels and 2012.

Name	County	Well ID	Aquifer	Latitude	Longitude	Highest chloride level (ppm)	Chloride level in 2012 (ppm)	Chloride level difference (ppm)	Year of highest water level
Chicod	Pitt	O 23L4	Black Creek	35.46364	-77.275	50	35	15	2007
Chicod	Pitt	O 23L8	Lower Cape Fear	35.46364	-77.275	1099	758	341	2007
Grifton Ball Field	Pitt	P 24O1	Lower Cape Fear	35.3711	-77.409	369	352	17	2010

Table 8 continued. Chloride levels for each well during the year with the highest chloride levels and 2012.

3.6: Shortcomings

3.6.1: Data analysis approach

The limitations of the data analysis approach are that the interview process was conducted ten years after the stakeholder process concluded, and thus participants were either not available to be interviewed or participants' recollections of the process may have been clouded due to lapse in time. Furthermore, the interviews lacked quantitative information that could allow robust statistical techniques to be applied to the qualitative data. Despite these limitations, the results of this study are of value because additional information (e.g. archival data) was used to corroborate the interpretations derived from the interview process. In addition, the time lapse between the inception of the process and the evaluation allowed for accrual of substantial groundwater level data provided through an expanded groundwater monitoring program. These data were crucial for establishing the effectiveness of the management policy in reducing the imbalance between groundwater abstractions and recharge.

3.6.2. Rule making process

Although the stakeholder representatives were chosen to involve "all legitimate stake-holding interests" (Morse, 2010), certain major users of water in the Central Coastal Plain (e.g. a large water district) were not invited to directly participate as a member of the stakeholder committee. Thus, as noted in correspondences from non-participating entities, some of the major players neither experienced a growing understanding of the problem nor did the players feel that the solutions that were proposed to solve the water management problem were financially equitable. Once the rule was finally implemented, large water districts had to make large financial investments to address any shortfalls to anticipated future reductions in water supply.

A major shortcoming of the development of the CCPCUA rule was that the stakeholder representatives found the process and outcome fair, whereas the broader stakeholder group found the outcome as unfair. After the stakeholder committee rule was adopted into law, the segments of the groups excluded from the process expressed dissatisfaction with the final outcome even though they were amply represented in the stakeholder committee. The announcement of the final rule (which caught some of the stakeholder groups unaware) was accompanied by cries of “unfunded mandate” from the stakeholder groups that were not involved in the process (Wilson, personal communication, 2009). In contrast to the stakeholder representatives, those dissatisfied with the outcome did not have the comprehensive background to completely grasp the magnitude of the problem or the scientific information driving the need for the regulation. In the stakeholder committee meetings, the technical advisors effectively communicated the issues, problems and consequences of certain actions to the stakeholder representatives. Yet, the stakeholder representatives did not have the time, or the skill set to brief their constituents about the evolution of the process. Consequently, the State agency found itself in the unenviable position of publicly defending the regulation (crafted by the stakeholder representatives) and educating the populace outside the formal rulemaking process (which included the broader stakeholder group) after the CCPCUA rule making process had ended. Other researchers (e.g. Maguire and Lind, 2003) found bias and lack of confidence in a similar process employed to regulate water quality in an eastern North Carolina watershed. Because public involvement and education in the decision-making process is vitally important (Margerum, 2011), a process that does not include such a mechanism ultimately leads to various groups feeling alienated and dissatisfied. These lessons suggest that, although it is unrealistic to believe that laypersons are capable of accurately conveying complex technical information, a mechanism that allows for periodic information exchange to stakeholder constituents during the rulemaking process should be an important consideration during early planning phases. A less compressed time frame that allows for broader stakeholder groups to meet with technical advisors could alleviate the education gap between those within and those outside the rule making process.

In response to objections raised about requiring farmers to report water withdrawals to the State agency, the final regulation made concessions for agricultural activities although agriculture is an important user of water in the Coastal Plain (Figure 8). The representatives from the agricultural sector argued that farmers be held to standards based on their level of knowledge and financial resources or be allowed to submit estimates of production based on historical uses for similar operations (Peele, personal correspondence, 4/10/2000). Based on this recommendation, the final rule created a new category of users of water (i.e. intermittent users) who are not subject to reductions, but do have to apply for a permit, and report withdrawals and water levels. Intermittent users of water are defined as those that (a) withdraw water for less than 60 days per year or, (b) withdraw less than 5.7 x 104 m^3 (15 million gallons) of water per year. In addition, the draft rule allowed agricultural users to report withdrawals to a State or Federal agricultural agency, rather than the State resource agency to which all other major users of water were required to report withdrawals. The removal of agricultural users from the same permit and withdrawal reduction process implied a favored status and created the feeling of an unfair burden placed on all other stakeholder groups.

3.7. Model for global application

A model illustrating the major elements of the themes discussed in this research is presented in Figure 14. The model, which represents a fair process that follows the principles of procedural justice and effective and enforceable management policies, can be applied in other regions across the globe experiencing water imbalances. Included in the model are phased groundwater withdrawal reductions, permitting based on withdrawal volumes, expanded monitoring program, well retrofit programs, new, innovative and state of the art technologies, construction of new and updated facilities, use of alternate water sources, conjunctive water use, development of new fields, interbasin transfers, and conjunctive water use (Nelson 2012). As documented from the case of the CCPCUA, the results of an inclusive rulemaking process and implementation of an acceptable groundwater management policy are sustainable aquifers which are characterized by rebounding water levels (Appendix C), acceptable water quality and low groundwater withdrawals.

Figure 14. Conceptual model illustrating themes of process, policy implementation and sustainable aquifers.

3.8. Summary and conclusions

Well-intentioned attempts to manage water resources without allowance for stakeholder representatives' input are usually contentious and unsuccessful (Ostrom et al., 1999; Borsuk et al., 2001; Maguire and Lind, 2003; Maguire, 2006). However, stakeholder representative participation alone (i.e. a participatory process) is not enough to guarantee a successful process and outcome because only representation and voice/participation are guaranteed in such a process. Stakeholder group participation should therefore include a procedural justice framework that does not only encompass the elements of a participatory process but also includes the overarching themes of respect, fair treatment and impartiality as they pertain to the ‘rules and processes of resource allocation’ (Leventhal, 1976, 1980).

Rapidly declining water levels (Appendix C), saltwater intrusion, and low well yields were reasons to construct a regulatory tool to manage water in the Coastal Plain of North Carolina. Although few denied there was a problem in eastern North Carolina in need of a solution, there was much disagreement for the best solution to solve the problem. Initial proposals were viewed as unfunded mandates with lack of public input, and burdensome regulations with poor enforcement powers. After several aborted attempts to obtain community support, the environmental State agency realized the importance of following fair and equitable procedures to resolve the impasse.

Diverse groups of participants with conflicting priorities were initially at odds, but through a fair and just process, they were able to build workable relationships. To construct acceptable regulation, facilitators incorporated lessons from social and organizational psychology, and socio-legal studies to a protocol that gave voice to participants representing a diverse group of stakeholders. The CCPCUA was a collaborative, procedurally just process in which stakeholders’ opinions, needs and concerns were addressed. In the end, the process resulted in a much better rule than originally proposed. The development of the CCPCUA regulation was an innovative, integrative and efficient use of process and people. It produced a straightforward regulation that was acceptable to the majority of users and, as a result, enforceable.

It is difficult to develop protective regulations for a commons resource that stakeholder groups find both just and effective (Ostrom et al., 1999). Therefore, it is instructive to understand the successful implementation of procedural justice to invest end-users and policymakers in resource strategies. The ability to have respectful input and unbiased facilitation translates to reasonably accepted outcomes important to resolution of resource protection and allocation conflicts (Lind, 1995; Rohl and Machura, 1997; Deutsch, 2000; Borsuk et al., 2001; Brockner and Wiesenfeld, 2005; Muller and Kals, 2007). All are invaluable aids in forming consensus. As presented in this study, and supported by the literature (e.g. Lind, 1988; Lind, 1995), given a reasonable outcome, participants frequently view the process as important as the outcome. The initial failed attempts at rule making illustrated that, although it is vital to integrate science with policy, science does not easily translate into management policy. Good policy is one in which stakeholder groups are supportive and willing to comply; otherwise, it is ineffective and unsustainable (Borsuk et al., 2001; Maguire and Lind, 2003; Maguire, 2006).

As growing populations put more demands on natural resources, the sustainability and management of water resources will create greater conflict. The creation of the CCPCUA regulation highlights a successful collaboration using a fair, just and inclusive process. Not only was the process successful, but the rule achieved its intended goal of protecting aquifers from degradation.

4: ADAPTIVE MANAGEMENT: FROM SAFE YIELD TO RESILIENCE THROUGH THE LENSE OF EQUITY

Key points

- Advances interdisciplinary research; socio-economic-hydrology.
- Moves beyond concept of simple water balance and safe yield.
- Proposes a comprehensive framework that allows resource managers to quantify .and adapt to rapidly changing environmental, social and economic conditions, while relating specifically to groundwater resources.
- Borrows concepts from other disciplines.
- Employ backcasting.

4.1. Continuing journey from safe yield

In 2004, Alley published, *The journey from safe yield to sustainability* in the journal Ground Water. In the article he acknowledged that strategies for groundwater management have changed to encompass the interconnections of ecological and social systems. This dissertation contributes to the evolving field of groundwater management by suggesting a paradigm shift from the stagnant concept of safe yield to suggesting water management tools based on equity. The idea of equity relies on interdisciplinary concepts that consider groundwater management through a systemic, multi-criteria approach.

The CCPCUA regulation was based on the concept of safe yield, considering a simple water balance maintaining withdrawals less than the recharge (Heath and Spruill, 2003). “Safe” is a subjective descriptor shaped by personal experiences and perspectives. In 1915 Lee described safe yield as the amount of groundwater that could be withdrawn from an aquifer “regularly and permanently without dangerous depletion of the storage reserve.” Meinzer, often referred to as “the father of modern groundwater hydrology” (Hackett, 1964), added the idea of human use and economic feasibility. Todd (1959) appended Meizner’s definition to include annual withdrawals causing “undesired effects” to the aquifer. The conversation among hydrologists with respect to the meaning and usefulness of the concept of safe yield has been ongoing since Theis (1940) first discussed the idea of aquifers in dynamic equilibrium. Numerous authors (Conkling, 1946; Thomas, 1951; Banks, 1953; Burt, 1967; Bredehoeft et al., 1982; Bredehoeft, 1997; Sophocleous, 2000; Bredehoeft, 2002; Alley and Leake, 2004), have altered the original definition of safe yield and have gone so far as to call for its complete elimination (Kazmann, 1956). The USGS no longer includes safe yield in their glossary of definitions. Management decisions made based on safe yield, alone had the potential to advance environmental needs above social and economic concerns. When the Brundtland Commission redefined the goals for natural resource management to fulfill “the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987), they introduced the idea of weighing environmental, social and economic considerations to create acceptable solutions. Sustainability is now a more generally accepted management model, tying the physical aquifer response to the environmental, social and economic interactions. Sustainability looks at responsible development through resource management, with one eye on the present and another toward the future. The concept does not view the environment in a vacuum, separate from human interactions; yet it is a stagnant concept that does not account for changes to the systems (Benson and Craig, 2014). Unfortunately, sustainability often compromises the most vulnerable groups and factors. The idea of resilience accepts environmental, social and economic changes and proposes ideas for recovery from those changes. Resilience is also defined by the capability of an aquifer system to avoid short term, long term or permanent damage. However, resilience approaches do not take into consideration the needs and demands of humans. Nor does it consider the numerous, site specific links between the social, physical and economic factors impacting groundwater management.

Until the term “safe” can be given an unbiased and objective definition, a reasonable approach would be to manage natural resources from the viewpoint of equity, considering issues of “fairness, equity and flexibility” (Simms, 1989). Equitable apportionment, as defined by the US Supreme Court, or by extension, equitable management is “a flexible doctrine which calls for the exercise of an informed judgement on a consideration of many factors” (Colorado v. New Mexico, 1982). The Colorado case refers to surface water, however it is a theme of this research that the many factors of managing water applies to groundwater, as well. In Nebraska v. Wyoming (1922), the court realized the many factors involved with water management and stated the relevant factors cited “indicate the nature of the problem of apportionment” (i.e. management) “and the delicate adjustments of interests which must be made.” Just as the US Supreme Court has used equitable apportionment doctrine that governs interstate surface waters, an equitable management policy for ground water would consider the multi-dimensional criteria involved with managing a commons resource for the common benefit of all systems (environmental, social and economic), considering the impacts, harms and benefits to those systems (Bernadett, 2014). Equitable apportionment, safe yield, or any water management policy are evolving strategies, influenced by modern environmental knowledge and law. Ultimately, any resource management choice must weigh the cost-benefit of those choices. As it is a delicate balance between the environmental, social and economic considerations, these factors must be considered and adopted into adaptable management strategies for groundwater resources.

This research supports a further transition from safe yield, sustainability and resilience to propose a management theory that incorporates equitable management of groundwater resources. Evaluating water resources in terms of equity acknowledges the ever changing and interdisciplinary nature of groundwater management. In an attempt to consider the many factors involved with managing water, researchers have applied numerous methodologies, including hydro-sociology (Falkenmark, 1979), social-ecological systems (Berkes and Folke, 1998), water resource management, integrated water resource management (UN Water Conference 1977), adaptive water management, hydro-economic modelling, coupled human natural systems (National Research Council Board on Sustainable Development, Policy Division, 1999), socio-hydrology (Sivapalan et al., 2012), and One Water (Mukheibir et al., 2014; US Water Alliance, 2016; Paulson et al. 2017). The field of hydrology now frequently considers the interactions between hydrologic processes and humans (Vörösmarty et al., 2010, 2013), ecology (Lui et al., 2007), economics (Heinz et al. 2007), or society (Sivapalan et al., 2012). All of these integrated approaches address broader water management directives. Each of the considerations impacting the management of water is inextricably linked. This research incorporating equity continues to advance the integrative nature of analyses by avoiding past approaches which have focused on separate analyses for each discipline, often with a predisposition toward the researcher’s field of expertise (Blair and Buytaert, 2016).

4.2. Refining management for groundwater resources

The work conducted in this chapter lead to the publication of an article in a peer reviewed journal article. Refining management strategies for groundwater resources, Hydrogeology Journal https://doi.org/ 10.1007/s10040-014-1177-2.

4.2.1. Introduction

Accessible potable water resources are imperative to global health. However, despite years of management interventions, groundwater resources remain threatened by overexploitation and contamination due to (a) increasing human population, (b) urban, industrial and agricultural development, and (c) climate change and sea level rise. Population dynamics accompanied by climate change will place greater stresses on groundwater resources and lead to increased threats of pollution, salt-water intrusion, and declining water levels due to withdrawal of large groundwater volumes (Green et al., 2011; Taylor et al., 2013).

The ultimate goal for resource managers is sustainability. Regardless of the resource, sustainability has become the buzzword for environmental health, yet is a difficult term to understand (Sophocelous, 2000). In 1987, the United Nations defined sustainable development as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). This view, wisely calls for both a short and long-term perspective for resource management. It also begs the difficult incorporation of criteria measured in qualitative and quantitative terms with inconsistent measurement units (Ashley, 2008; Ryu et al., 2009). Yet, it is a shortsighted and human-centric view driven by human needs. In contrast, Alley et al. (2002) defined groundwater sustainability as the “development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences.” This broader view incorporates all aspects of the environment, including, but not limited to humans.

The literature is rife with broad descriptions and examples of interventions for resource sustainability (e.g., Alley et al., 1999; Sophocleous, 2000; Alley and Leake, 2004; Alley and

Leake, 2004; Unver, 2007; McCarthy, 2008; Ryu et al., 2009; Mukheibir, 2010; Sophocleous, 2010; Gleeson et al.,201; Mays, 2013). Many of the strategies are cross-disciplinary and are not groundwater specific (e.g., Deming, 1986; Blumenthal and Jannink, 2000; Ambler, 2002; Ashley et al., 2008; Mihelcic, 2008; Petrini and Pozzebon, 2009; Stainer and Stainer, 2009; Weidmann et al., 2009; Leon-Soriano et al., 2010). However, a comprehensive framework that allows resource managers to quantify and adapt to rapidly changing environmental, social and economic conditions, while relating specifically to groundwater resources is lacking. Here, we borrow concepts from other disciplines and argue that refined and flexible groundwater management philosophies incorporating proven methodologies can help model, develop and evaluate groundwater resource strategies. We suggest that major organizational changes are required to meet the challenges of temporally and spatially changing groundwater supplies and demands. We reexamine basic groundwater management norms to include strategies to maintain variously scaled projects, over both short and long timescales while incorporating changing environmental, social and economic conditions. Only through a steadfastness of intention, improved groundwater use, evaluation, and management philosophies coupled with efficient resource practices, resource allocation, and pricing, will water managers successfully achieve groundwater sustainability.

In addition to well-established groundwater management protocols (e.g., Alley et al., 1999; Gleick, 2003; Sophocleous, 2010), we propose the following elements vital to achieving sustainability: 1) well-defined long-term goals for the future with varying temporally and spatially measurable benchmarks (Vision), 2) innovative management strategies (Adaptation and Integration), 3) empowerment and education (Cooperation), and 4) incorporation of new water supplies, interconnections, and innovative technologies and pricing (Diversification and Innovation).

4.2.2. Vision

A well-defined, long-term vision for the future must provide a strategic approach to resource protection that includes long-term aspirations, incorporating environmental, societal and economic factors (Ashley, 2008; Gleeson et al., 2012) and comprise dynamic short-term goals or objectives for sustainable development of groundwater resources. Well-defined visions and adaptable expectations are best established at the onset of the strategizing process. These visions, accompanied by well-established timelines, allow for reflection and re-evaluation of future conditions. Backcasting (i.e., designing strategic solutions for a present problem from a future perspective with an idealized vision of success) (Figure 15) is a useful strategic starting point, yet is a static prognosticator of strategic planning. Unless frequent evaluation opportunities are included in strategic planning, backcasting does not account for dynamic environmental, social or economic conditions impacting resource management. As an alternative, we suggest incorporating a “just good enough” (Ambler, 2002) approach into strategic resource planning for groundwater resources. This idea, derived from agile modeling (Ambler, 2002), uses less rigid, iterative, and adaptable dynamic models to create moving visions for the future. In these types of models, just good enough benchmarks and short-term goals are altered and adapted to evolving conditions based on vision changes. Because each model is more refined than the previous iteration, subsequent models are sufficient for achieving short-term goals, while maintaining focus on long-term visions (Figure 15).

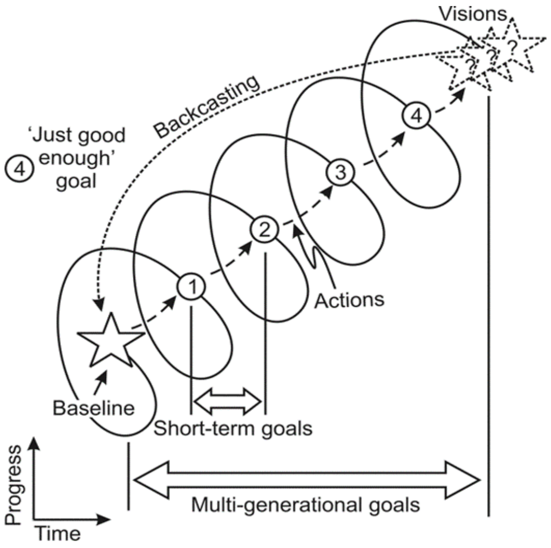

Figure 15. Iterative process of making progress from a given baseline or problem to the vision.

4.2.3. Adaptation and integration

Effective management strategies should include innovative and iterative processes of goal setting, strategy implementation, monitoring, re-evaluation and strategic revisions (Figure 15). Just good enough goals, described above, may be sufficient on the short-term, however, without incorporating measurable outcomes and action triggers, implemented management strategies may not be flexible enough to adapt to changing conditions. Thus, multi-generational timelines (Gleeson et al., 2012) are acceptable when the management plan incorporates flexible points of re-assessment and modification. Continually monitoring changes in the environmental, economic and social conditions and devising evaluation plans and benchmarks at various time scales can then inform policy decisions for water resources management (Gritsinin, 2008). Instituting a monitoring and/or research plan that periodically gauges the progress to specific goals is a necessary step for realizing the overall vision. Only through flexible adaptive management, taking into account continually evolving physical, social and political realities, will management policies maintain public health, ecological stability and economic growth (Blumenthal and Jannink, 2000; Ashley, 2008).

4.2.4. Cooperation

A significant hurdle to the successful management of fresh water resources is abuse of water stemming from society’s view that water is a common property resource (Ostrom, 1999). Such views, especially important when resources span geopolitical boundaries, often lead to exploitation of common resources as people use resources with sole consideration for their own self-interests (Hardin, 1968). This hurdle, in part, is surmountable through dialogue and collaborative decision-making.

Different disciplines have their own verbal shorthand and jargon that result from common experiences. The common language that develops among discrete groups is often misunderstood by others (Palmer et al., 1997), creating a language barrier that handicaps communication between policy makers, water managers, stakeholders and end-users (Arkema, 2006). Effective communication must produce accessible information if there is to be constructive discourse to solve problems, cause action, and deal with consequences. This is especially true when communicating technically and economically difficult issues, such as resource allocation and management. Resource advisors (e.g., scientists) can help those unfamiliar with technical implications of issues and solutions (e.g., water managers, stakeholders and end-users) to develop a common and straightforward language and reduce miscommunications. Un-biased facilitators, involved early in the strategy development process, can help resolve unfavorable perceptions and/or results. We contend that the interaction and cooperation of various groups with differing skill sets, viewpoints, knowledge and needs is especially successful when participants have clear responsibilities and non-overlapping roles.

Cooperation is central to an interactive and integrated policy in which diverse and conflicting factors (i.e., factors affecting all sectors of physical and social communities) are considered. In resource management, cooperation is a sophisticated and complex adaptation of the “prisoner’s dilemma” in which acting on self-interests or strictly human interests, to the exclusion of the broader ecological and geopolitical community, results in diminished benefits to both the individual and the community as a whole (Rapopert and Chammah, 1970). Cooperative management of all facets involved with the resource (i.e., environmental, social, economic) ultimately leads to fairness, efficiency and sustainability in resource development, allocation and protection.

4.2.5. Diversification and innovation

Matching users’ needs with water availability is imperative for successful management strategies. This not only involves creating new sources of high quality water for end users, but expands the use of lesser quality water, to meet diverse needs (Cook et al., 2010). Conjunctive water, grey water and rainwater utilization can expand the productivity of currently available water supplies. Developing new water supplies, interconnections and innovative technologies relieves the strain on single water sources, while strategic diversification focused on supply and demand policies, encourages reclamation, reuse, conservation and education to effectively use, wisely manage, and invest end users into protecting all available water resources. Innovation and diversification need not be limited to management strategies. Innovative and adaptive pricing structures will stimulate investment in infrastructure, industry growth, environmental protection, conservation and equitable access.

4.2.6. North Carolina (USA) case study

Until the latter part of the twentieth century, fifteen counties in eastern North Carolina (NC) counties relied, almost exclusively, on Cretaceous aquifers as their water source. Historically, this east dipping and thickening sedimentary section of unconsolidated units provided high quantity, quality water. Although the aquifers extended into other states, growing populations in NC caused increasing demands and groundwater withdrawal climbed sharply. Coupled with low recharge, these once prolific aquifers experienced a severe imbalance between withdrawal and recharge rates, causing declining water levels and greater salt-water intrusion (Heath and Spruill, 2003). To ameliorate the growing problem, the state of NC in collaboration with its citizens developed the Central Coastal Plain Capacity Use Area (CCPCUA) and enacted protective regulations to manage groundwater resources. We use the CCPCUA as an example of how the elements of the iterative and adaptive strategy described above (i.e., vision, adaptation and integration, cooperation and, diversification and innovation) were incorporated to develop and implement the CCPCUA groundwater management plan.

The CCPCUA regulation required "just good enough" goals to halt falling water levels. These benchmarks and short-term goals proposed the reduction of groundwater withdrawal by 25% between 2002 and 2008, and 25% reductions in each of the next two 5-year time periods, for a total reduction of 75% by 2018. Embedded in this attempt at backcasting, were short-term benchmarks evaluated at the end of each period following reduction. Although the CCPCUA monitoring system assessed changing conditions, strategic goals were not adjusted to take into consideration the aquifer response. Ultimately, the inability to set new benchmarks based on new information (e.g., physical response of aquifer) was a shortcoming of the strategy. The information at the end of each reduction period was neither fed back into the loop, nor were the goals and vision adjusted based on economic, social and environmental changes. Although the CCPCUA is on its way to stabilizing water levels and saltwater invasion, there was never a well-developed vision for healthy Cretaceous aquifers. This lack of qualifying metrics (e.g., water levels and chloride concentrations) caused confusion between regulators and end users, discontentment between water providers, unnecessary expenditures, and missed economic opportunities.

Many changes have come about in response to the CCPCUA including investments in alternate water sources, interconnections, and the utilization of advanced technologies. Conservation is an important outcome of the CCPCUA, with public water providers now reporting details on existing and proposed conservation actions, including pricing incentives, irrigation guidelines, water loss reduction, retrofit, public outreach and education, and practicality of water re-use programs.

4.2.7. Conclusions

Refined, flexible groundwater management strategies incorporating diverse approaches are required to tackle groundwater resource problems in the face of climate change and increasing global populations. Here, we present a case study that illustrates the importance of disparate geopolitical entities agreeing on common problems before solutions can be adequately addressed. The study shows that there need not be an aquifer-wide control of the resource as a necessary pre-condition for successful implementation of the proposed management framework. Rather, the control ought to occur where the resource is most vulnerable.

The CCPCUA case study demonstrates how proven concepts are applicable to global groundwater sustainability. We contend that successful groundwater management involves metrics that assess not only the physical response of aquifers, but also the social and economic responses to new groundwater management strategies. The assessment of these metrics should be included in an iterative protocol that allows for shifting short and long-term goals established by backcasting. Alternate perspectives that place different values on water encourage conservative and innovative uses of water to guarantee groundwater sustainability.

The ideas of vision, adaptation, integration, cooperation, diversification and innovation presented here are in the context of a common-sense synthesis of successful ideas from other disciplines (e.g., business, computer modeling, socio-legal studies, organizational psychology etc.). Until recently, resource managers have focused on the natural sciences to solve multi-dimensional resource issues, however, we believe the management philosophies suggested here, incorporating successful methodologies from fields outside of hydrology will help create flexible frameworks with which to model, develop, evaluate and protect groundwater resources.

5: EQUITY BASED MULTI-CRITERIA DECISION ANALYSIS FOR GROUNDWATER MANAGEMENT: A SUITABILITY ANALYSIS OF THE 2002 CENTRAL COASTAL PLAIN CAPACITY USE AREA

Abstract

A multi-criteria decision analysis process is used to examine a groundwater management scheme designed to address declining water levels and saltwater intrusion in the Central Coastal Plain of North Carolina. Suitability and geospatial analyses aid in the assessment and identification of areas most vulnerable to changes in groundwater pumping strategies. Publicly available data is used in the analysis process to create thematic layers based on six criteria that impact groundwater management decisions (e.g., population, socioeconomic factors, aquifer properties etc.). Using geospatial techniques to manipulate these layers, regions that are able to withstand changes to groundwater management schemes are identified through a Suitability Analysis. Regions with low values represent areas that are more vulnerable to changes in management schemes, whereas regions with high values represent areas less impacted by changes in management schemes. The Suitability Analysis identifies several previously unidentified areas that are less capable of withstanding changes to groundwater management strategies.

Whereas, the CCPCUA management strategy solely considered the hydrologic conditions of the aquifer at the time of the rulemaking, the results of the Suitability Analyses simultaneously consider six hydrologic and socio-economic factors. Although the hydrologic characteristics remain the driving criteria, the tool, based on these six interacting factors, provides viable alternatives to the single criteria method for managing groundwater. The results of the Suitability

Analysis of the CCPCUA suggests that there are many areas in the CCPCUA that would be managed differently had this approach been adopted.

This study suggests a philosophical shift in approaching groundwater management issues. Previous management schemes in the CCPCUA have viewed solutions based on hydrologic conditions, whereas solutions derived from suitability analyses are based on multi-criteria. Multi-criteria decision analysis is a sustainable management approach resulting in aquifer protection while continuing to provide for the current and future needs of the stakeholders.

Key points

- Advances a Suitability Analysis tool which identifies areas capable of withstanding changes to groundwater management strategies.
- Proposes a transparent, inclusive, and quantifiable groundwater management tool
- Compares areas identified through two different evaluation methods as suitable for changes to pumping strategies.
- Identifies areas which may be negatively impacted by changes in pumping strategies.

5.1. Introduction

Multi-criteria decision analysis (MCDA) was originally conceived to develop business schemes for which there are “multiple conflicting objectives” (Zionts, 1979), multiple potential solutions, and a myriad of conflicting influences with many dissimilar units of measure (Hajkowicz and Collins, 2007; Hajkowicz and Higgins, 2008). As such, decision making is an historic struggle of how to balance the trade-offs of “pros and cons”. MCDA originated from management research as an instrument through which these trade-offs are quantitatively and objectively evaluated (Zionts, 1979; Hajkowicz and Higgins, 2008). Over the last forty years MCDA techniques evolved with the onset of automated computer technology, which has aided in the ability to graphically assess, display, and communicate the many problems and solutions (Foreman and Gass, 2001).

Although conceived for business applications, MCDA has been used in a wide variety of fields to develop appropriate courses of action and formulate policy options (Zionts, 1979). MCDA has advanced beyond the business arena to become a valuable tool to develop natural resource strategies. MCDA is an effective tool for natural resources, as the pressures on resources, especially water, are numerous. Proven concepts from diverse fields are applicable to global groundwater sustainability (Klein, et al., 2014) and illustrates how successful groundwater management schemes involve all criteria that impact groundwater. The following multi-criteria assessment is a part of an iterative process that encourages evaluating new information, back-casting, and refining short and long-term goals. Figure 16 shows the types of data for the MCDA conceptual model for use in the Suitability Analysis tool.

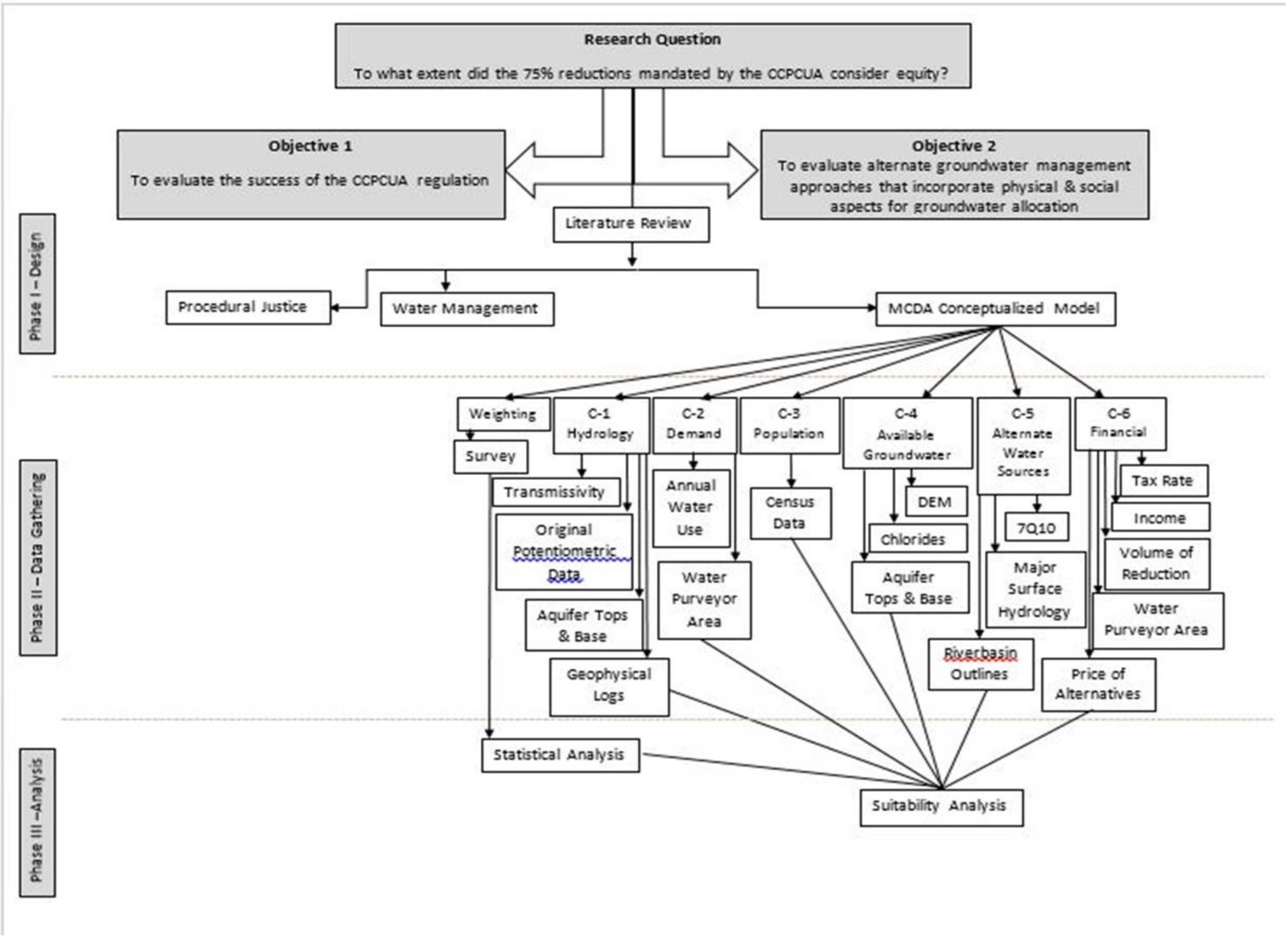

Figure 16. Protocol for creating the MCDA conceptual model.

By their nature, natural resources are impacted by multiple criteria, imperiled by competing physical, social and economic stresses. By considering the physical and socio-economic demands, groundwater managers adopt an equitable approach to sustainably managing aquifers. The physical considerations include understanding hydrologic components of the aquifers while extending the longevity of those systems. The social concerns include the basic requirements for life (i.e., adequate food, potable water, sanitation), as well as the psychological desire to experience fair treatment while having a voice in impactful decisions that impact the quality of one's life. The economic demands involve maintaining groundwater supplies without overly burdensome financial costs to maintain systems. The ideal management scheme is one in which the anthropogenic needs balance with physical and biological sustainability. A multi-criteria decision analysis approach taken for this research suggests an equitable mechanism to meet the multitude of often conflicting hydrologic, social and economic demands on groundwater reservoirs. Using MCDA to incorporate procedural justice, adaptive management, volumetric analyses, and equity criteria, this research provides a transparent tool for evaluating, analyzing and integrating multiple criteria to make complex decisions.

Although there are a variety of approaches to MCDA, there are several common components (Geng and Wardlaw, 2013).

- identification of solutions
- identification of criteria
- assessment of the solutions

In the case of the Central Coastal Plain Capacity Use Area (CCPCUA), the solutions involve identify low, medium and high areas able to withstand changes to groundwater management tactics. Six criteria are identified, as suggested by the United Nations Convention on the Law of

Non-Navigational Uses of International Watercourses (United Nations, 1997), impacting water resource management. The solution assessment relies on geospatial analyses, the Analytical Hierarchy Process (Appendix B) and Suitability Analysis.

MCDA techniques (i.e. Suitability Analyses) combined with user friendly geospatial analyses greatly improve the transparency and detail involved with creating informed and effective management policies (Tomlin, 1990; Store and Kangas, 2001). MCDA incorporates the many factors that affect groundwater sustainability and drive management scenarios. The geospatial analysis platform allows the researcher to manage and manipulate the multiple criteria input layers to create new composite layers and scenarios.

5.2. Suitability analysis

Suitability Analysis is an MCDA tool aimed at determining sites for future protection, utilization or development, including land, habitat, environmental, geological, landscape, resource development, planning, and protection (Hopkins, 1977; Moreno, 1988; Bonham-Carter, 1994; Miller et al., 1998; Collins et al., 2001; Brail and Klosterman, 2001; Klosterman, 2001; Store and Kangas, 2001; Kalogirou, 2002; Malczewski, 2004). Suitability Analyses define the acceptable extent of development or utilization of spatial areas (Brookes, 1997; Malczewski, 2004; Xiao, 2002). Geospatial analyses are used to assign ranks or scores to discrete spatial units (McHarg, 1969; Steinitz et al., 1976; Malczewski, 2004; Waters, 2002). The Suitability Analysis informs management strategy, and validates strategic decisions based on a multitude of criteria and objectives (Malczewski, 2004).

As used in this research, the outcome of Suitability Analyses is identified spatial areas that merit exploitation or protection. In combination with geospatial tools, the results are clearly displayed, and compared to the pumping withdrawals mandated by the CCPCUA regulation. The outcomes described serve as a model for future strategic planning.

Suitability Analysis concurrently examines various criteria by integrating multi-criteria data while considering different perceptions, scales, and outcomes. Originally performed to create landscape plans, a series of thematic maps displaying different attributes of the area are vertically superimposed. The stacked input maps are compiled and incorporated into a single outcome map (McHarg, 1969).

Geospatial analysis is a management and manipulation tool used in MCDA analyses to integrate data from diverse sources into spatial displays (Berry, 1993; Malczewski, 2004). Geospatial analyses assemble a comprehensive picture of geographic information through a sequence of thematic spatial maps (Malczewski, 2004). The three main uses of geospatial analysis (Malczewski, 2004), as used in this research, are:

- Storing and accessing data
- Integrating data
- Support for decision making

The first hand drawn, transparent, overlay landscape maps from the early twentieth century have evolved into computer assembled, geospatial analyses maps (Malczewski, 2004) created as visualization tools (Jankowski et al., 2001). Yet, the science of Suitability Analysis has moved beyond simple input and visualization of technical data. Management and planning strategies now use Suitability Analyses by incorporating socio-economic and hydrologic data with concepts of procedural and environmental justice (Longley et al., 1999; Collins et al., 2001; Malczewski, 2004). The inclusion of equity in this research further advances the application of the Suitability Analysis tool.

The input to the Suitability Analyses are thematic maps which represent the attributes of each criteria; the factors considered important when developing solutions to suitability problems. Numerous groundwater management criteria impact groundwater sustainability and use. Although not an exclusive list, six criteria are chosen for this research. These criteria are adapted from international guidelines on water resources, the Berlin Rules (ILA, 2004), modifications of the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (United Nations, 1997). The six relevant criteria are: 1) hydrogeologic characteristics, 2) demand, 3) population, 4) available groundwater, 5) availability of alternate water sources, and 6) financial ability to fund alternate water sources.

The following sections (5.2.1-5.2.6) define the criteria used for the comparison of the outcomes of the 2002 CCPCUA regulation to the equity based, multi-criteria decision analysis as developed for this research. The methodology for creating each criteria layer is discussed in Appendix A.

5.2.1. C-1 Hydrology

The hydrogeologic characteristics of aquifers are often the driving factors considered when formulating management strategies. The 159 water professionals surveyed perceived hydrology as the single-most important criteria for crafting groundwater management strategies. For the purposes of this research, hydrology or hydrogeologic characteristics are dependent on two important aquifer characteristics, transmissivity and safe drawdown.

The transmissivity of an aquifer is the rate at which water moves through a unit area of a material (either an aquifer or confining bed) under a unit hydraulic gradient in a set period of time (Freeze and Cherry, 1979; Fetter, 1988; Heath, 2004). It is dependent on the properties of the water, the conductivity and the gross thickness of the material.

Safe drawdown represents a lowering in the potentiometric surface without causing detrimental harm to the aquifer (Todd, 1959). Safe yield and safe drawdown are subjective measurements and represent different ideas to different water professionals. Although measured in different units, safe yield and safe drawdown both indicate changes in the aquifer system. Safe yield is the amount an aquifer can "economically and legally" be drawndown "on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environmental damage" (Fetter, 1988). As used in this research, safe drawdown is the vertical distance a potentiometric surface can be lowered without compromising the sustainability of an aquifer. Defined in similar terms, groundwater sustainability is "development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley et al., 1999). What constitutes unacceptable consequences varies by the temporal and spatial circumstances (Alley, et al., 1999). Sustainability is defined as that which "meets the needs of the needs of the present generation without compromising the ability of future generations to meet their own needs (Brundtland Report, World Commission on Environment and Development, 1987)."

Toward the end of the 20th century, the NCDEQ became alarmed about the sustainability and the economic viability of the Cretaceous aquifers when the number of wells increased, and the wells experienced observable changes, including lower volumes, "pumping air" (Wilson, personal communication 2008), continuous and precipitous water levels declines, and salt water encroachment (Morris, Wilson, personal communications, 2008). At the time of the rulemaking, NCDEQ's strategy was to establish an estimate of the recharge rate as a proxy for safe yield, however, the NCDEQ deemed the well monitoring network inadequate to provide sufficient data for a model (Morris, Wilson, personal communications, 2008). There is still no definitive recharge value for the Coastal Plain and the NCDEQ did not establish a tangible threshold of recharge as the critical marker for safe yield. Therefore, this research suggests reconsidering the concept of safe yield as a determinant of aquifer sustainability and instead suggests the adoption of safe drawdown. Further discussion of safe drawdown or of a sustainable aquifer will assume that the maximum safe potentiometric surface drawdown is to the top of the aquifer. The rules of the CCPCUA regulation recognize this, as it stipulates that the pump intakes must be located above the top of the confined aquifer to prevent dewatering (CCPCUA, Section .0502).

5.2.2. C-2 Demands

There is a difference between demands and needs (Gleick, 1998). Water demands are the wants or the requests of a community to fulfill the requirements of a comfortable life (Gleick, 1996; Gleick, 1998). Whereas demand is what is important for a society to maintaining a healthy, economically productive and adequate quality of life (World Bank Water Demand Research Team, 1993; Gleick, 1996; Gleick, 1998), needs are a basic requirement necessary for survival (Gleick, 1996; Gleick, 1998; Lukasiewicz, 2017). When considering criteria for the equitable management of groundwater, this research assumes that existing potable water supplies are sufficient to meet the basic requirements of life and that the demand reflects the quality and quantity of water for which communities within eastern North Carolina are willing to pay for a healthy and productive existence.

Globally, water demands are diverse and change as populations migrate, industries move, and agricultural production evolves. The Coastal Plain is no exception. Although demand for water in the Coastal Plain has not appreciably changed, the way those demands are met has, out of necessity, shifted. While managers once focused on long term groundwater development, the emphasis is now on managing demand, providing continued water security and sustaining all available resources to meet those demands, regardless of the merit of the demands. The demands considered for this research are only those required by society, and although the environment is an important stakeholder (Starik, 1993; Jacobs, 1997) placing demands on the groundwater, it is not considered here.

5.2.3. C-3 Population

Population and population densities are important criteria, as communities are a large stakeholder group placing demands on groundwater resources. In North Carolina, more than 50% of the major water use is for public water supply (NCDEQ). With approximately 37% of the total water use in the CCPCUA allocated for public water supply (Figure 17), equitable distribution of water is crucial (NCDEQ).

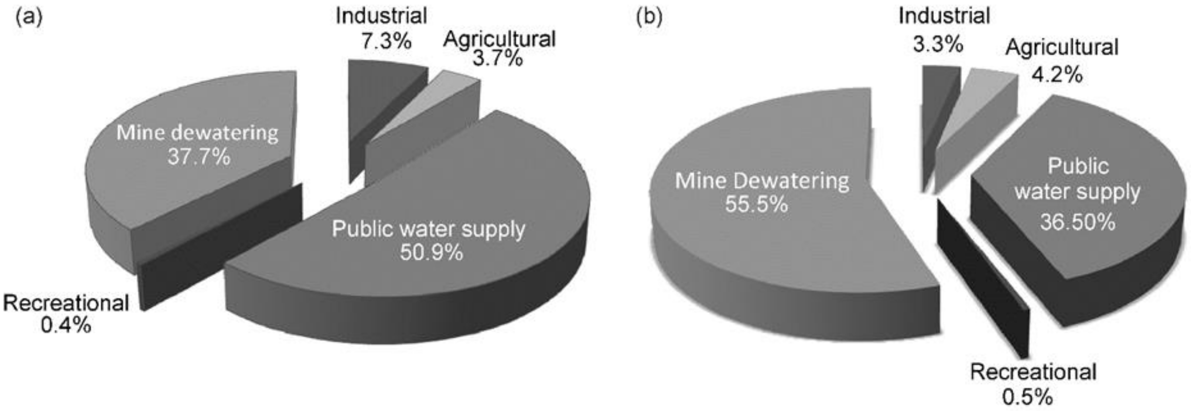

Figure 17. Water use in North Carolina and in the CCPCUA.

In the past, communities, industries, and agriculture flourished and developed near available water resources. Communities were able to obtain sufficient potable water supplies from a combination of surface and groundwater sources within close proximity. Technological changes and financial considerations have made it possible for populations to grow and develop far from available resources. As populations migrate there becomes a mismatch between where the populations grow and where the resources are available. The philosophy for water development has become, out of necessity, to develop water where accessible and move it to where it is needed (personal communication R. Spruill). Therefore, it is important to accurately identify the spatial distribution of populations.

Between 1970 and 1990, the total population in these counties increased by 20% from 695,598 to 834,718 inhabitants (http://www.census.gov), with a discernable population imbalance across the Coastal Plain. Although the vast majority of the area is rural, the largest growth occurred in population centers. Approximately 38 % of the world's population lives within 100 km of the coast (Kay and Adler, 1999), and much of the population in eastern North Carolina is concentrated near the coast. Yet, much of the North Carolina coastal residents are seasonal, making it a difficult place to develop an equitable management scheme based solely on population.

5.2.4. C-4 Available Groundwater

The most prolific aquifers in the Coastal Plain are the Lower Cape Fear, the Upper Cape Fear, the Black Creek, the Peedee, the Castle Hayne and the surficial aquifers. The Lower Cape Fear aquifer is locally developed as a resource, but overall of poor quality. The Peedee formation, the uppermost Cretaceous aquifer, is shallow and of lesser quality than the Black Creek and Upper Cape Fear aquifers. Compared to other Cretaceous aquifers, the Peedee has less available drawdown, high concentrations of iron and total organic carbon, and higher treatment costs (Heath and Spruill, 2003). The Eocene aged Castle Hayne Formation is the most prolific aquifer in the CCPCUA, but also suffers from overuse (Reynolds and Spruill, 1995). Although all of the aquifers contain salt water, either as formation water or as salt-water intruded wedges (Lautier, 2006), the Quaternary surficial aquifer is unreliable along the coast and on the barrier islands as it is highly saline and affected by salt water intrusion and tidal salt-water influxes

(Lautier, 2006). This research uses the Black Creek and the Peedee aquifers as the other aquifers do not have as much groundwater data available as these two.

5.2.5. C-5 Alternate water source, surface water

Due to the restrictions for groundwater withdrawal imposed by the CCPCUA regulation, many providers have turned to surface water as alternate water sources (http://www.ncwater.org). As of 2017, there are at least seven surface water intake locations in the CCPCUA (Figure 18), with an additional facility under construction. Surface water is restricted in availability and quality which limits potential alternate surface water facilities. Several of the CCPCUA counties border the ocean or the sounds (e.g., Onslow and Carteret Counties), another potential surface water source, however, there is currently just one reverse osmosis (RO) plant (located in Carteret County) to treat saline water in the CCPCUA. For this research, only surface water will be considered as an alternate water source.

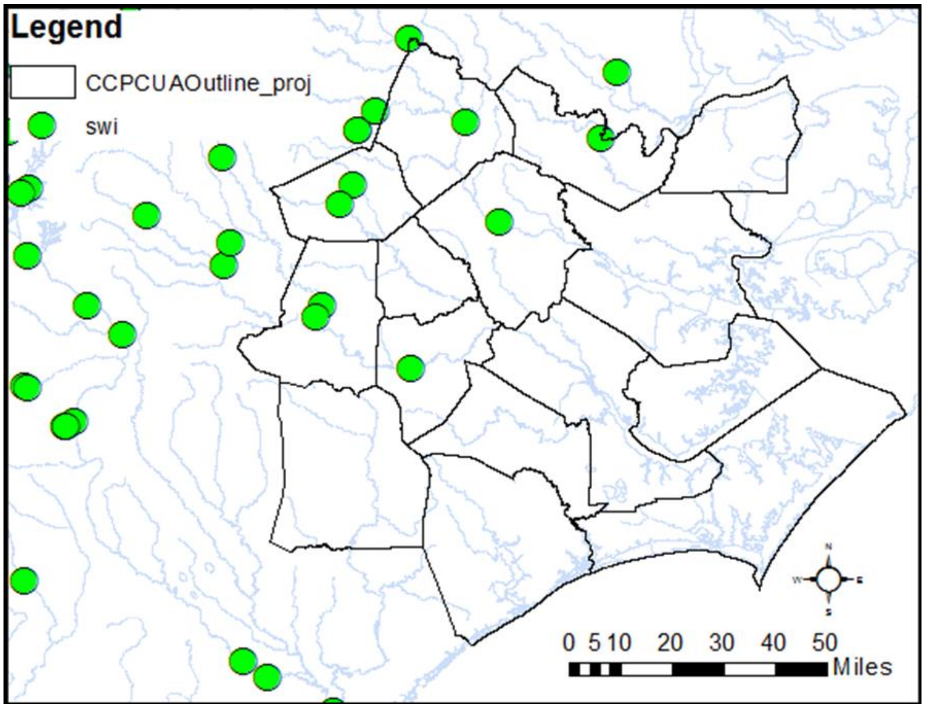

Figure 18. Surface Water Intakes in CCPCUA.

5.2.6. C-6 Financial ability to pay for alternate water sources

Water is an indispensable resource and, despite the fact that it is finite, it is a recycled resource. Unlike many other natural resources, it experiences continuous cycles of recharge and depletion (Hartwick and Olewiler, 1998). Despite the recyclable nature of water, the ability to provide sufficient potable water is integrally dependent on the financial capability of water providers to develop, operate and maintain water sources. If a reduction in groundwater pumping occurs, as in the case of the CCPCUA, and demand remains the same, or increases, the reduced water volume must be replaced through other economically viable sources. To replace those reduced volumes and continue serving consumers, service providers must utilize alternate sources of potable water. Turning to alternate sources is not without economic hardships. The objective of the financial analysis is to demonstrate the financial feasibility of utilizing alternate sources while protecting depleting groundwater resources. The CCPCUA case study develops an economic price tag for replacing groundwater supplies by calculating the hypothetical percentage change in the taxes needed to fund the water sources to replace the 30-75% reductions mandated by the CCPCUA.

5.3. Methodology

The process of determining suitable locations for changes in pumping strategies is performed using a Suitability Analysis process. The process includes:

- choosing relevant criteria
- obtaining attribute data for each criteria,
- developing geospatial layers for the attribute data
- reclassifying the data, assigning weights to each criteria (Appendix B)
- multiplying the reclassified attribute data by the weights

- summing the weighted criteria into one map to determine appropriate regions capable of withstanding changes to groundwater management schemes (Figure 19).

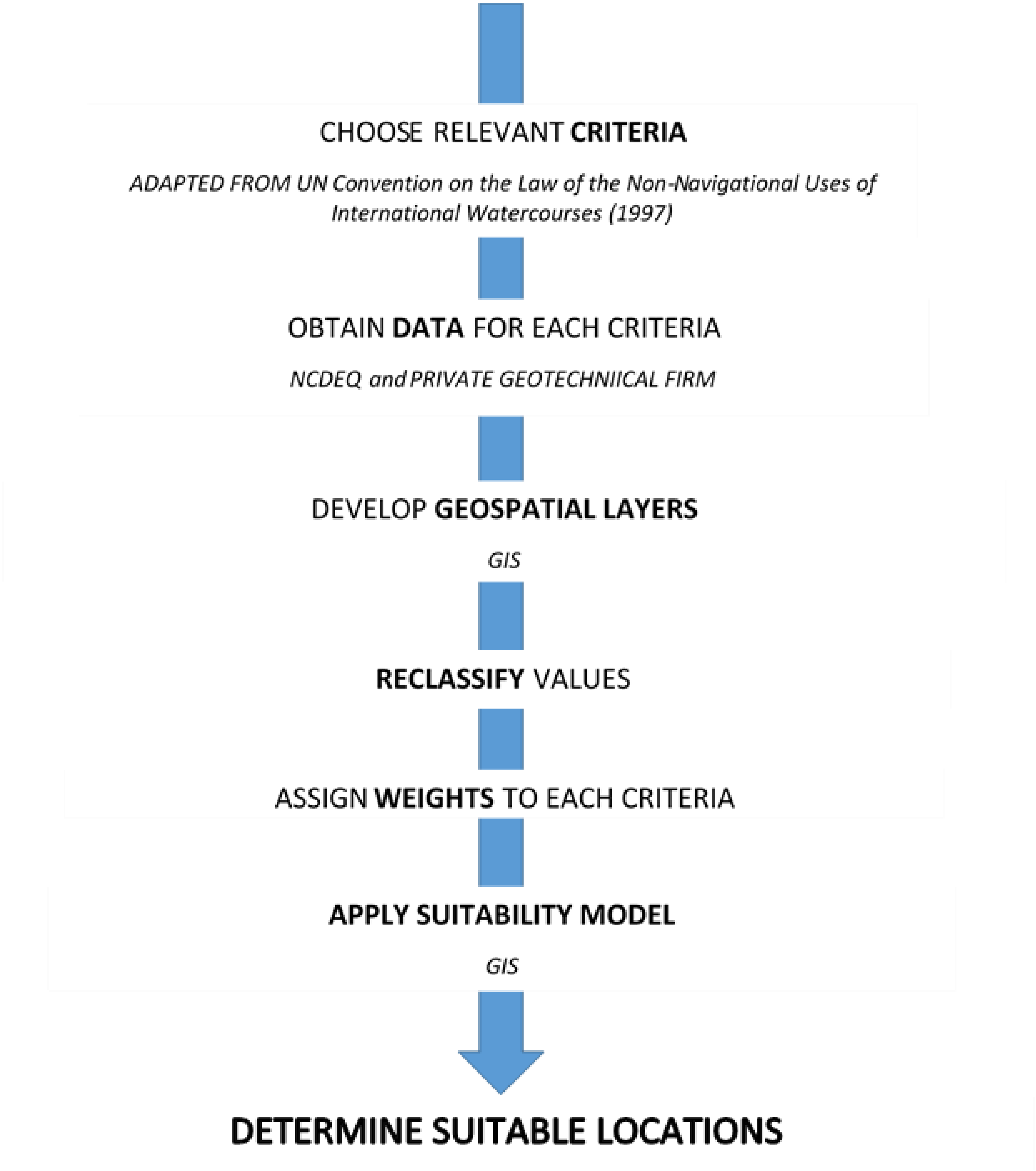

Figure 19. Protocol for Suitability Analysis.

This assembling and analyzing of spatial data uses the ESRI ArcGIS platform. All geospatial layers use the State Plane, NAD 1983 North Carolina FIPS 3200 (meters) projected coordinate system. Whenever possible, all water level data used for this project are for the time period closest to 2002, as the year 2002 represents conditions at the inception of the CCPCUA.

5.3.1 Developing geospatial layers from attribute data

Assessing suitable sites for groundwater withdrawals begins with obtaining and assembling attribute data for the criteria suggested by the UN Convention on the Law of spatial distribution of the attributes. For brevity, the processes of choosing, collecting and manipulating the geospatial layers are not included here. Rather, the interested reader is referred to supplementary materials for a detailed description of the procedures. Due to the differing nature and distribution of the attributes representing the criteria (e.g., limited availability of public information or lack of easily accessible data), different methods are used to create each thematic layer. The attributes of six criteria, each represented by a raster layer (Appendix A), are mapped for two of the major Cretaceous aquifers, the Peedee (Kpd) and the Black Creek (Kbc).

5.3.2 Reclassifying the attribute data

Attributes for specific criteria are often expressed in various units making it difficult to easily compare data. Therefore, it is necessary to change the raster values through a process of reclassification, in which there is a reassignment of values. Reclassified maps allow for a comparison of the attributes representing different criteria. Reclassifying the surfaces normalizes the layers and transforms them into thematic analysis layers with a common scale to create a single outcome layer.

The classification process involves grouping cells within percentile ranges. The different classes determine, for each particular criteria, areas capable of withstand changes to groundwater management strategies. For example, areas of high transmissivity (C-1) have a greater capacity to deliver water and therefore can withstand pumping reductions and are assigned to zone 3. Conversely, high demand (C-2) areas are assigned to zone 1, as the demands in that area are not negotiable and must be met.

Reclassification of the individual criteria maps assigns priority, or common grouped value levels to each layer for use in the Suitability Analyses. The reclassifications for each of the six criteria are as follows:

- C-1 Hydrology
    - Transmissivity
        - The lower the transmissivity, the more an area is impacted by changes to groundwater management strategies. Therefore, low transmissivity areas are reclassified as zone 1. High transmissivity areas are reclassified as zone 3.
    - Safe Drawdown
        - The smaller the safe drawdown, the more an area is impacted by changes to groundwater management strategies. Therefore, areas with low safe drawdowns are reclassified as zone 1. Large safe drawdown areas are reclassified as zone 3.
- C-2 Demands
    - The greater the demand, the more an area is impacted by changes to groundwater management strategies. Therefore, areas of high demand are reclassified as zone 1. Low demand areas are reclassified as zone 3.
- C-3 Population Density

    - The larger the population density, the more impacted an area is to changes to groundwater management strategies. Therefore, areas with large population densities are reclassified as zone 1. Highly populated areas are reclassified as zone 3.
- C-4 Available Groundwater
    - The less groundwater available to an area, the more impacted the communities are by changes to groundwater management strategies. Therefore, areas of low available groundwater are reclassified as zone 1. High availability areas are reclassified as zone 3.
- C-5 Alternate Water Sources
    - The less surface water available to an area, the more impacted the adjacent communities are to changes to groundwater management strategies. Therefore, areas of low surface water availability are reclassified as zone 1. Areas with high availability of surface water are reclassified as zone 3.
- C-6 Financial Capability to Develop Other Water Sources
    - Communities with a greater financial ability to develop alternate water sources are less impacted by changes to groundwater management strategies. Therefore, areas where taxes must be greatly increased to develop sufficient water resources are reclassified as zone 1. Areas with small increases to taxpayers to develop sufficient water resources are reclassified as zone 3.

The reclassified maps are included with the Appendix A.

For comparison purposes, the zone map, as defined by NCDEQ, was reclassified as follows:

- One (1), is assigned to the area of declining water levels. This area is subject to the minimum withdrawal reductions.
- Three (3), is assigned to the area of aquifer dewatering and salt water intrusion. This area is subject to the maximum withdrawal reductions.

5.3.3 Determining appropriate locations for management changes

The Suitability Analysis is an MCDA tool employed to determine the areas most appropriate for changes to management schemes. The specific Suitability Analysis method used for this research is a weighted linear combination (Hopkins, 1977; Tomlin, 1990; Carver, 1991; Malczewski, 2000; Malczewski, 2004) which uses equation 1 and is dependent on reclassified criteria attributes (Appendix A.1) and weights (Appendix B.3). Weighted site selection is preferred when different criteria do not have the same level of importance (Malczewski, 2004).

$$S' = \sum_{I=i}^{6} W_i C_i \qquad \text{(Eq. 1)}$$

Where:

S' = suitability of a location to withstand changes to groundwater management strategies

W_i = assessed weight of the criteria i

C_i = the reclassified criteria attribute

For each reclassified criteria layer, the raster values are multiplied by the weight of the criteria (Appendix B). These products are then summed resulting in an outcome layer that shows the areas that have high (i.e., high S' values) or low favorability (i.e., low S' values), to withstand changes to groundwater management strategies. The lower the additive value (S'), the less likely (i.e., more vulnerable) an area would be to withstand changes in pumping strategies. To determine the appropriate weights, a Likert-type survey was administered to 136 water professionals in various work sectors and locations across the United States. The results of this survey reflect the weights, or the relative importance, of the predetermined criteria for managing groundwater (Appendix B).

The 15 county CCPCUA area is assessed scores based on the suitability to withstand changes in pumping strategies. A score of 1 are deemed highly vulnerable and less suitable for changes in management strategies. A strategy of careful monitoring, with no reductions in withdrawals, might be recommended for these areas. Those areas assessed a score of 3, deemed less vulnerable and more suitable for changes in management strategies, might be candidates for rigorous reductions in withdrawals. Moderate changes to groundwater withdrawals might be recommended for areas identified with a score of 2. All areas, regardless of their S', should be closely monitored, with adaptations to the management strategies made as the hydrologic and socio-economic conditions change.

The resultant Suitability Analyses are represented by the following five layers:

1. The Suitability Analyses for the hydrologic criteria (representing the transmissivity and safe drawdown of the Peedee aquifer, the available groundwater, and surface water).
2. The Suitability Analyses for the hydrologic criteria (representing the transmissivity and safe drawdown of the Black Creek aquifer, the available groundwater, and surface water).
3. The socio-economic criteria (one map illustrating the socio-economic factors of demand, population density, and financial considerations).
4. The multi-criteria (representing all six, hydrologic, and socio-economic criteria for the Peedee aquifer).
5. The multi-criteria (representing all six, hydrologic, and socio-economic criteria for the Black Creek aquifer).

5.3.4 Process for comparing the suitability analysis results to the CCPCUA aquifer zones

Each of the five suitability scenarios are compared to the current CCPCUA regulation (Figure 20). To quantify the differences between the outcomes of the two approaches, the zone map was reclassified. The suitability layers were also reclassified into two categories to conform to the two categories of reductions mandated by the CCPCUA regulation. The two categories were divided by quantiles.

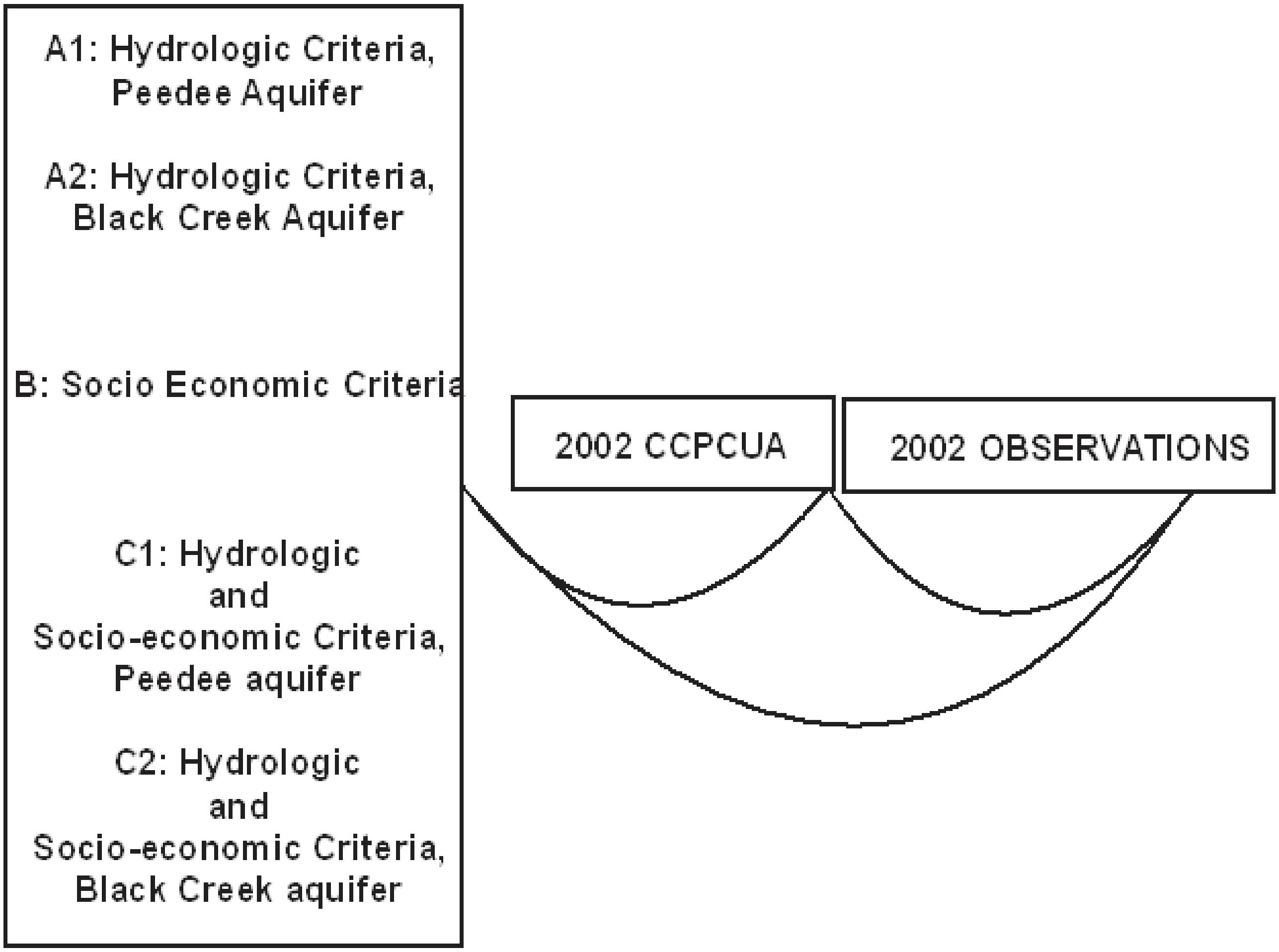

Figure 20. Protocol for comparisons of 5 sustainability analyses to that of the 2002 CCPCUA regulation and observations.

Using the ArcMap raster calculator, the suitability layers were subtracted from the reclassified zone map. Areas with a subtracted difference of zero represent areas where the two approaches agree on the ability to withstand changes in pumping. Negative values indicate areas where the suitability analysis deems more appropriate for reductions that the zone map. Positive values indicate areas where the suitability analysis deems less appropriate for reductions that the zone map.

5.4 Results and Discussion

The use of suitability analyses to assess aquifers initiates a new approach to groundwater; a holistic approach to water management in which the many criteria impacting groundwater are considered. For this analysis six equity criteria are considered, with the suitability analyses used to determine the areas best suited to withstand changes in management strategies (the areas identified with the highest S').

This is a marked change in approach to that of the 2002 CCPCUA management strategy. The 2002 regulation is based on the condition of the aquifer without regard for the aquifer or socio-economic characteristics. Areas of declining water levels are assigned pumping reductions of 30% (over the 16-year life of the regulation). This area is located on the west side of the CCPCUA in eastern Edgecombe, Wilson, Wayne, and Duplin Counties. A 75% pumping reduction is assigned to the areas experiencing dewatering and salt water intrusion, and encompasses most of Pitt, Greene, Lenoir and Jones Counties, as well as the west side of Beaufort, Craven, and Onslow Counties (Figure 21).

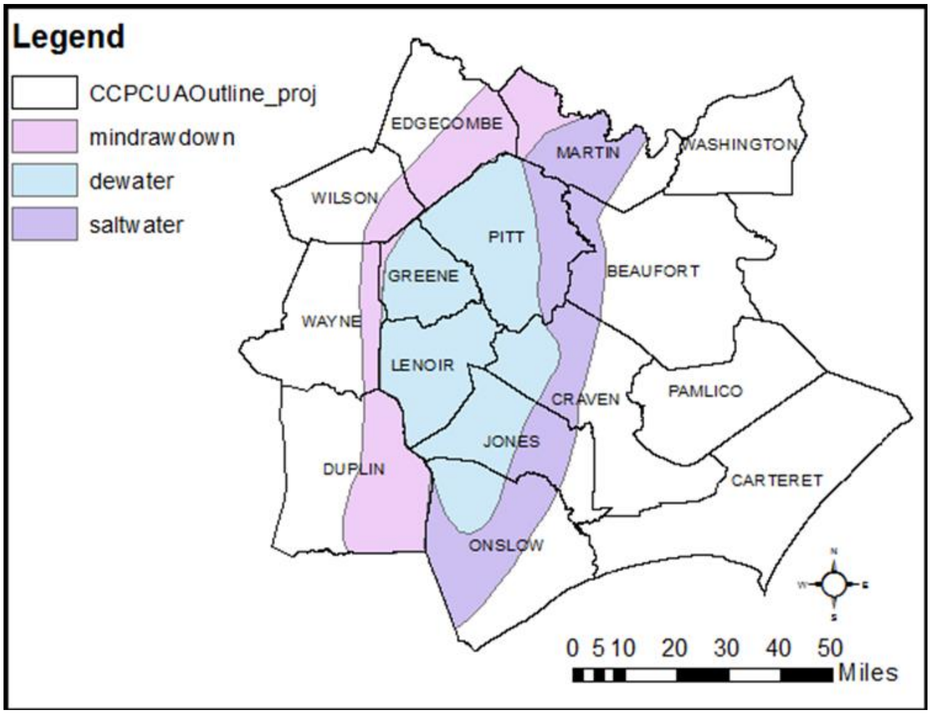

Figure 21. CCPCUA aquifer zone map (NCDEQ 2018).

5.4.1. Hydrologic considerations

The areas most suitable to withstand changes to pumping scenarios (high S’), based solely on hydrologic criteria, are similar for the Peedee and the Black Creek aquifers, as both have aquifer characteristics which improve to the east. Following the convention of transmissivity increasing with increasing aquifer thickness (Appendix A), the interpolated transmissivity values show an increase (Figures 22 and 23) as the two aquifers thicken, and hence higher S’ values, to the east (Figures 24 and 25). Safe drawdown also increases to the east and southeast for both aquifers (Figures 26 and 27), mirroring the dip of the aquifers and the potentiometric surfaces at the inception of the CCPCUA (Appendix A). Of note, the hydrologic characteristics take into account the transmissivity, the safe drawdown values, and the salinities of the aquifers. As such, the eastern area shown without color have chloride values greater than 5,000 ppm chlorides are not currently considered viable water sources without considerable treatment.

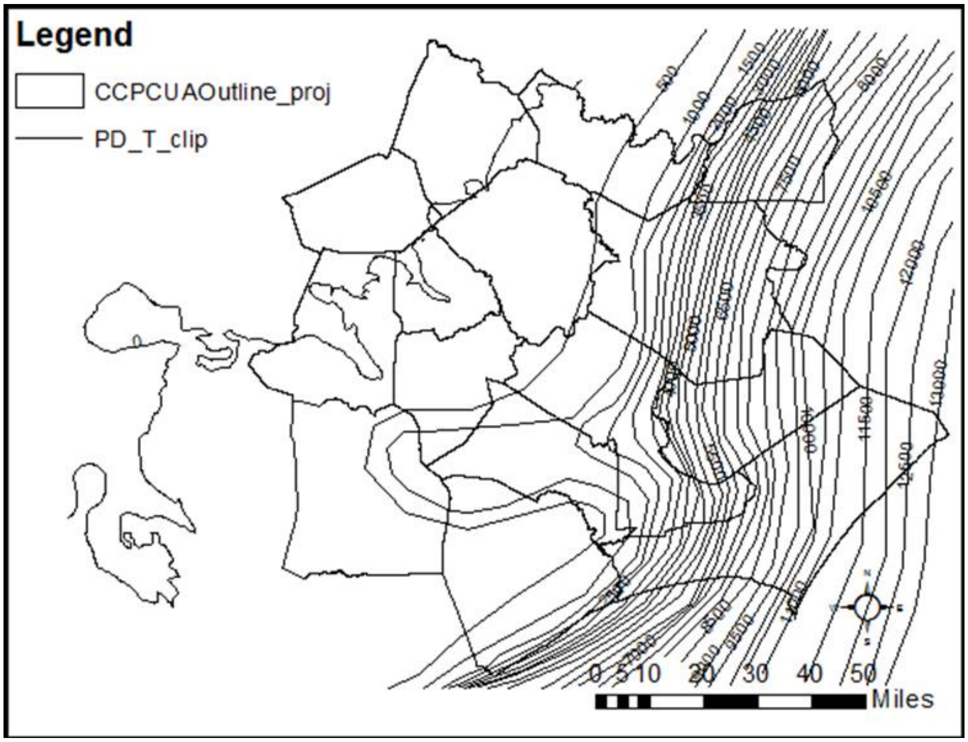

Figure 22. Transmissivity Peedee aquifer. C.I. = 500'.

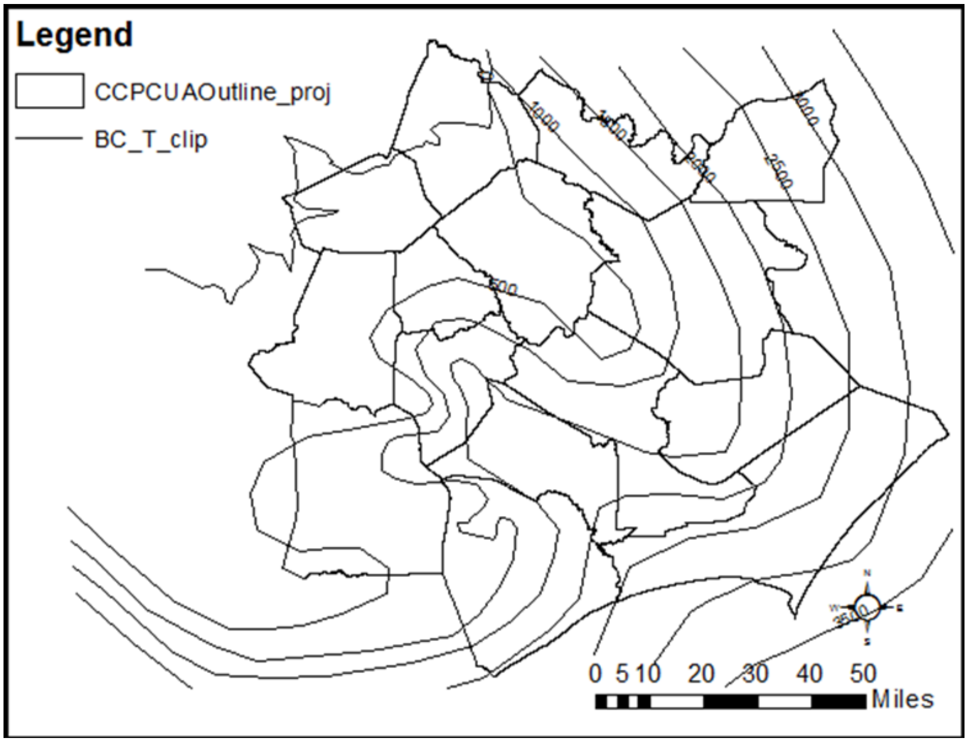

Figure 23. Transmissivity Black Creek aquifer. C.I. = 500'.

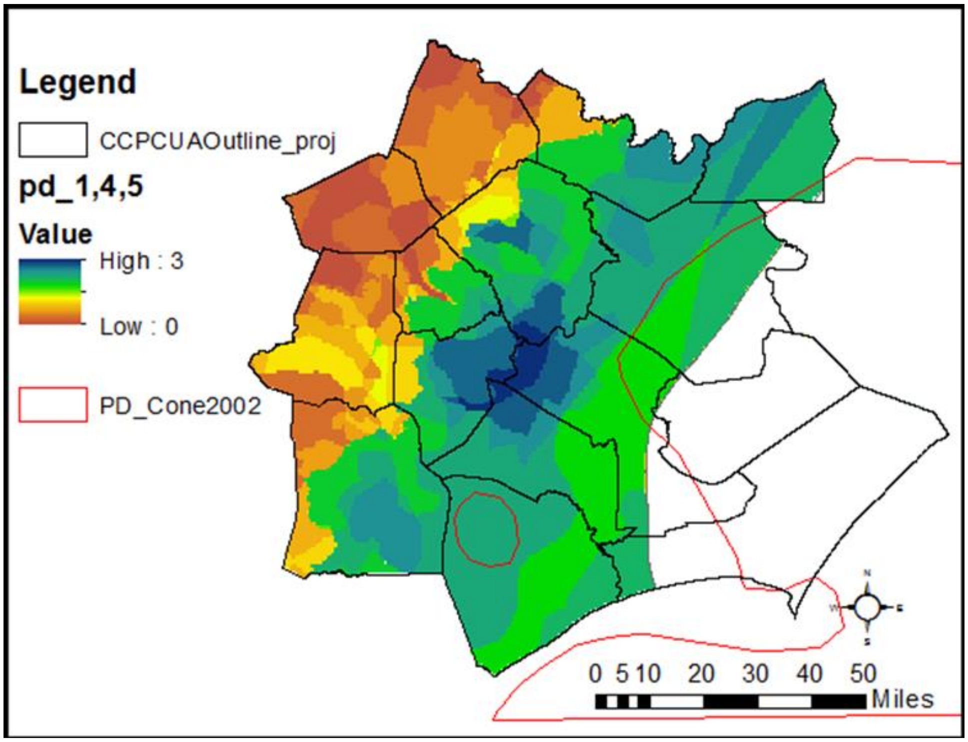

Figure 24. Suitability analysis map showing hydrological characteristics, Peedee aquifer.

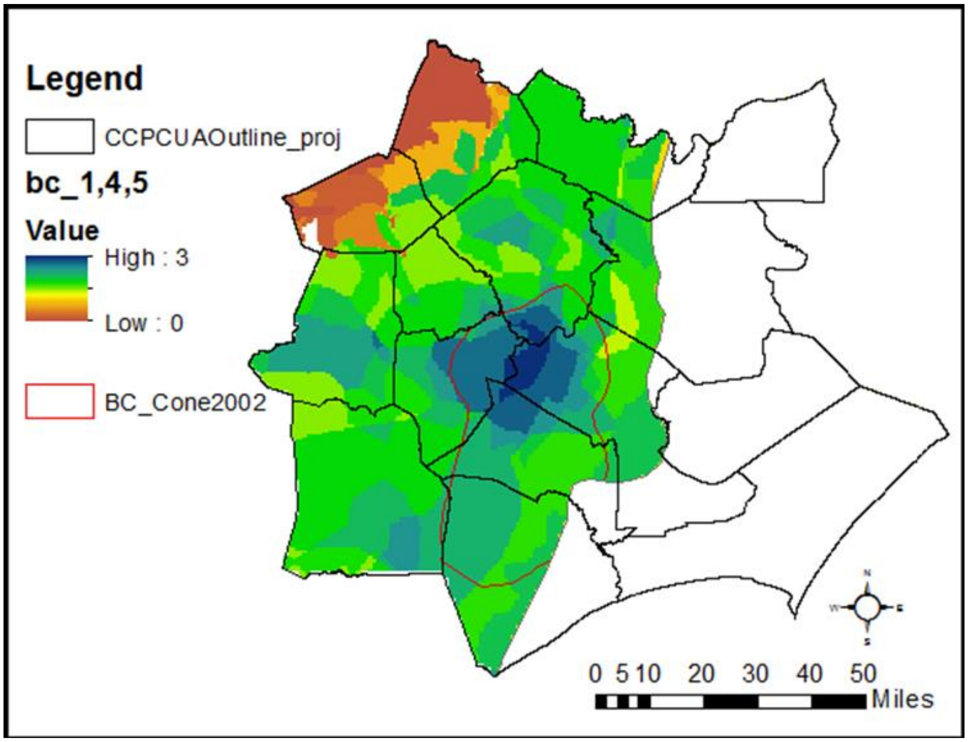

Figure 25. Suitability analysis map showing hydrologic characteristics, Black Creek aquifer.

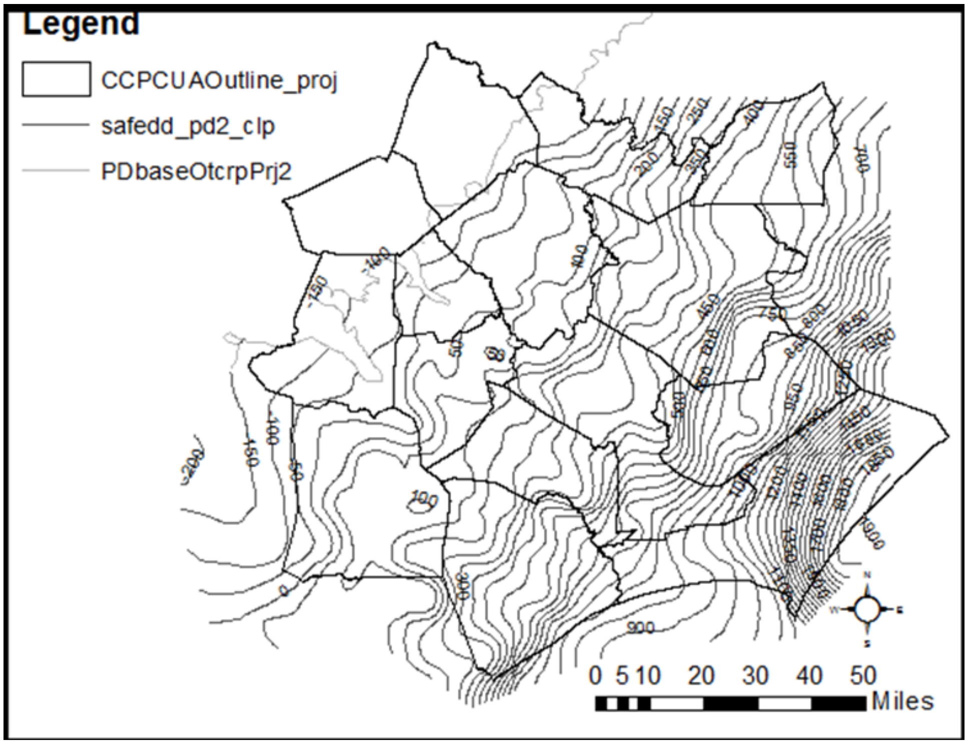

Figure 26. Isochore safe drawdown, Peedee aquifer. C.I. = 50’.

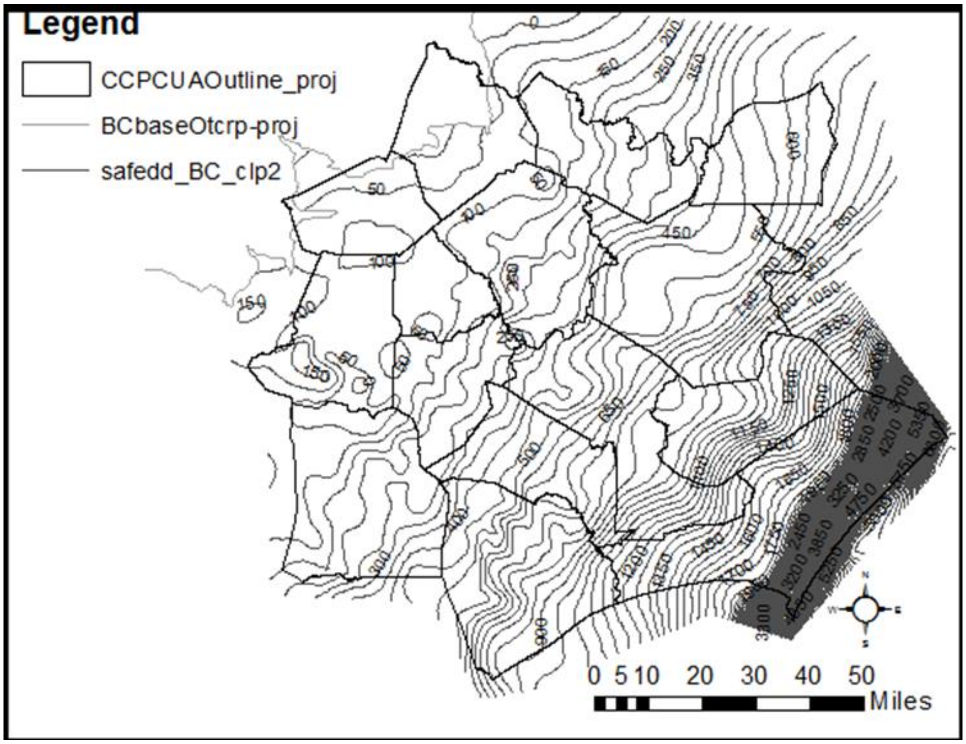

Figure 27. Isochore safe drawdown, Black Creek aquifer. C.I. =50'.

Based on the hydrologic characteristics, the areas most favorable (i.e., least vulnerable) for pumping reductions in the Peedee aquifer are located in southern and central Pitt, eastern Lenoir, northwestern Craven and northern Jones Counties (Figure 24). This area closely mimics the areas of maximum CCPCUA reductions (Figure 21). The CCPCUA reduction areas are based on aquifer conditions, with the more highly utilized aquifers forming a cone of depression, as identified by the 2002 NCDEQ potentiometric surface map (Figure 28), in the easternmost CCPCUA Counties and northeastern Onslow County.

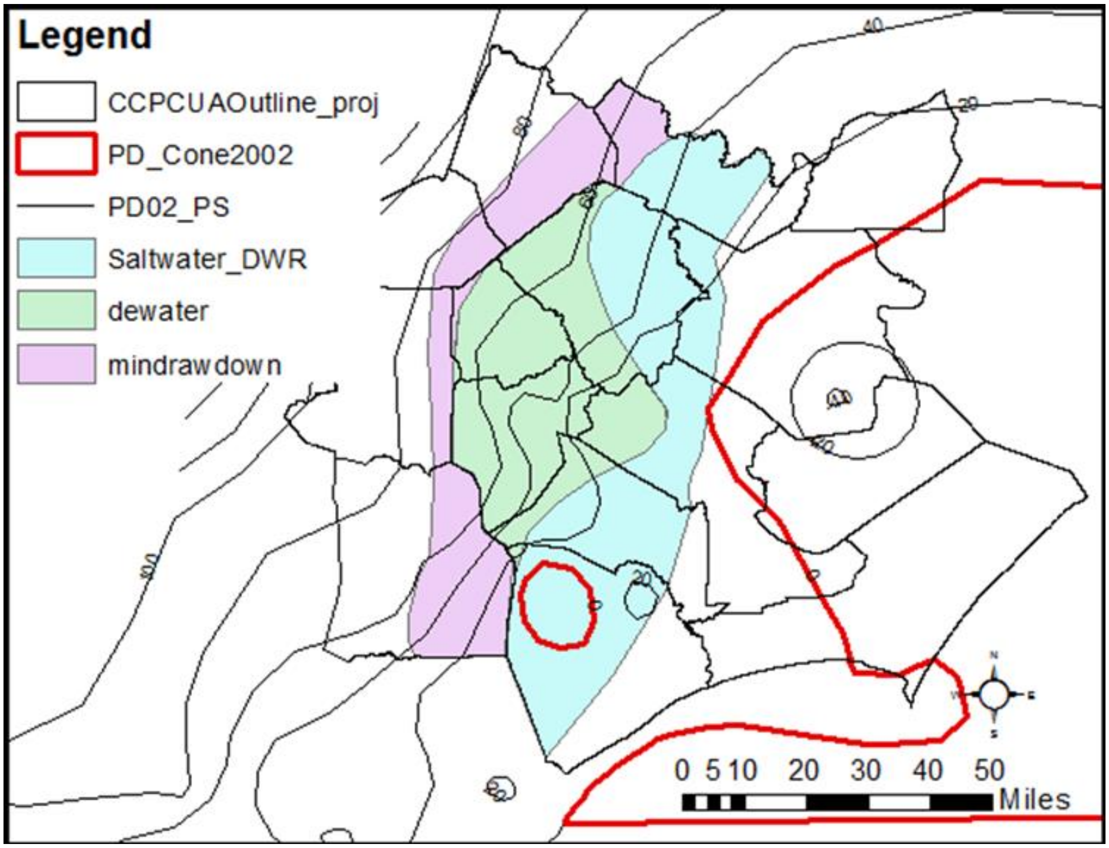

Figure 28. 2002 Peedee potentiometric surface, CCPCUA aquifer zones and cone depression C.I. =20'.

When considering the hydrologic criteria, C-1, C4, and C-5, the areas with high S’ values in the Black Creek (Figure 5.10) closely resemble that of the Peedee aquifer (Figure 24). The area highlighted by the current analyses aligns closely with the cone of depression as depicted in the

2002 potentiometric map for the Black Creek aquifer (Figure 29), which include western Onslow, Jones County and Craven Counties, southern Greene and the majority of Lenoir County.

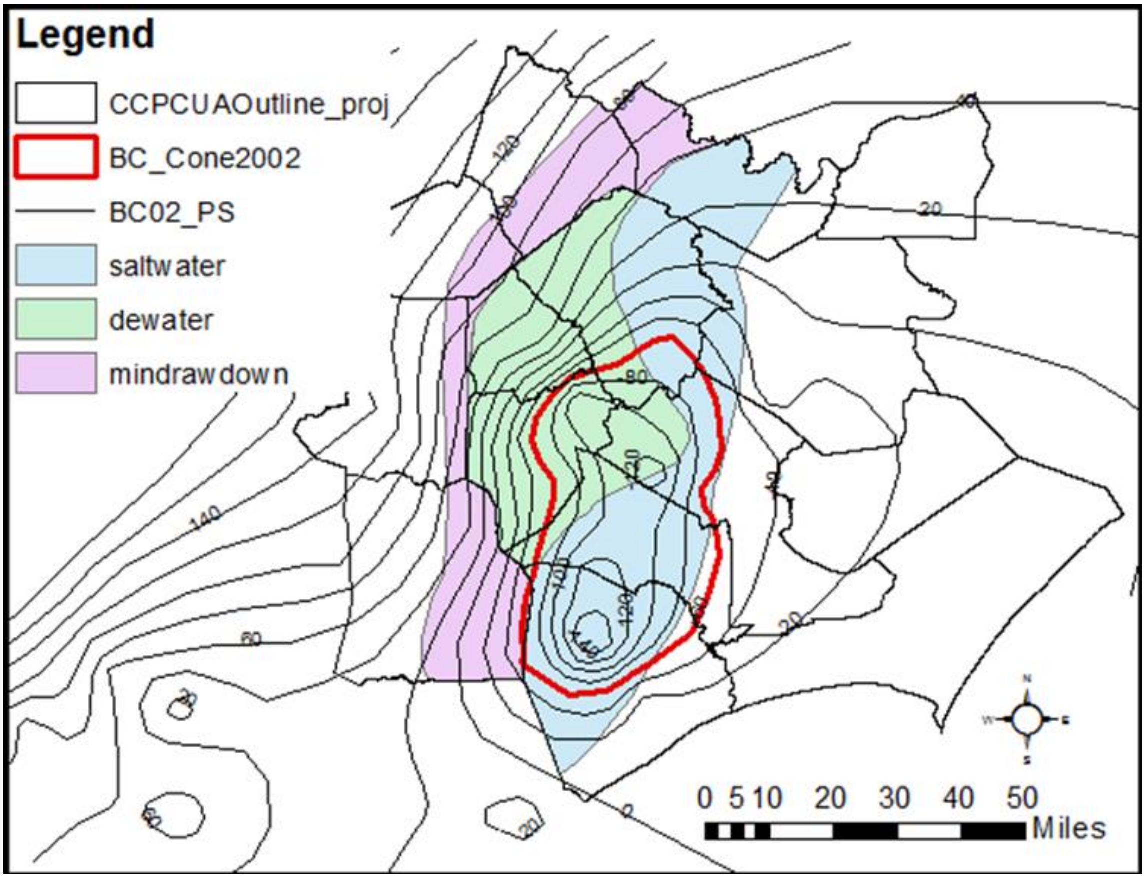

Figure 29. 2002 Black Creek potentiometric surface, showing CCPCUA aquifer zones and cone of depression. C.I. =20’.

The easternmost of Edgecombe, Wilson, Wayne, western Duplin, Greene and Martin counties are identified as the most vulnerable areas for the Peedee aquifer, following the Suitability Analysis of the hydrologic characteristics. In the Black Creek, eastern Wilson and Edgecombe Counties are deemed unsuitable for changes in pumping schemes. The areas designated as most suitable for changes in pumping schemes resulting from this analysis are similar to the areas denoted by the CCPCUA regulation. However, the counties in the western parts of CCPCUA, although mandated for reductions under the regulation, are not identified as suitable for reductions under the suitability scheme developed here. Whereas the CCPCUA regulation imposed the maximum reductions on all of Greene and Pitt Counties, and eastern Edgecombe, Wilson, and Wayne Counties, the current hydrologic analysis (based on transmissivity, safe drawdown, and available groundwater in the Peedee and Black Creek) score many of those areas as having low suitability for changes to pumping scenarios. These areas have low transmissivity, thin aquifers and small safe drawdown values. It is of note that two communities in this area have successfully challenged the reductions as mandated by the CCPCUA.

It is not surprising, however, that the areas that are identified as suitable for changes to pumping scenarios when considering the hydrologic characteristics look similar to those determined by the CCPCUA regulation as in need of reductions. The aquifer conditions observed in 2002 reflect the levels of use, with the largest withdrawals producing the most detrimental effects of pumping, and showing signs of declining water levels, dewatering and salt water intrusion. The areas of high use most likely developed because water was readily available due to the high quality of the aquifer properties and availability of surface water.

5.4.2. Socio-economic considerations

Using only the socio-economic criteria (demand, population density, and financial ability to pay for alternate water resources) the most vulnerable areas are associated with population centers. In most areas of the CCPCUA, the major water demands are for the areas with the highest populations. Therefore, the areas of low S’ (Figure 30) align with the areas of high population densities and include the larger communities of Greenville, New Bern, Kinston and Camp Lejeune/Jacksonville.

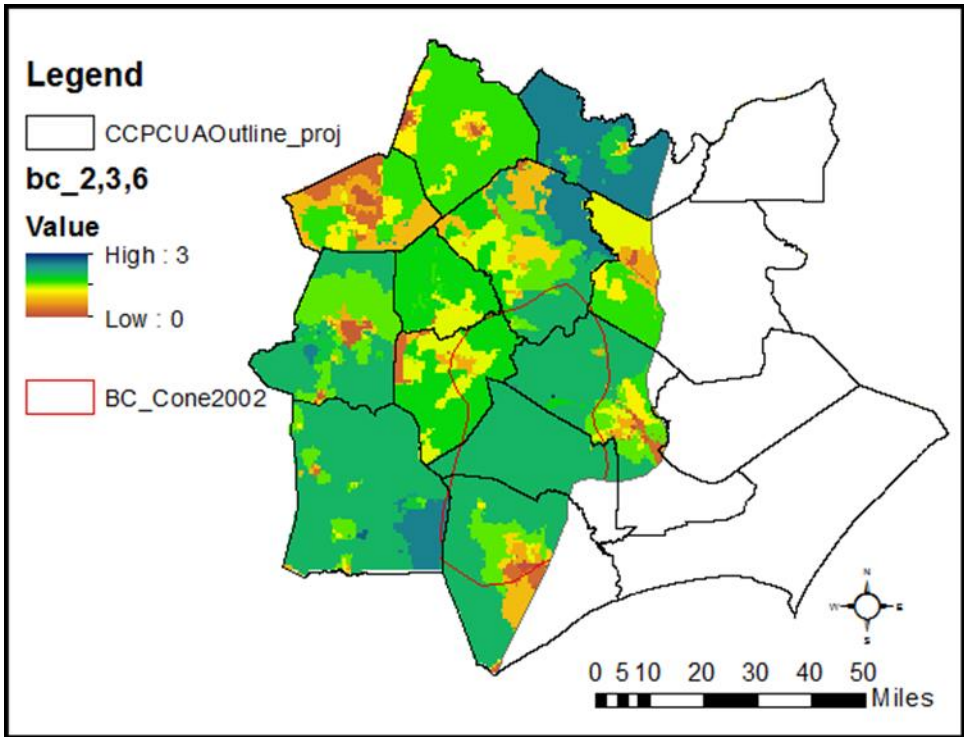

Figure 30. Suitability analysis map showing socio-economic characteristics.

For the Peedee aquifer, the cone of depression (Figure 28) lies adjacent to Camp Lejeune and Jacksonville. For the Black Creek, the 2002 cone of depression (Figure 29) lies between the areas of high population densities, and centers on Onslow, Jones and Craven Counties. The areas of highest S' are in rural communities where the population is smaller, and there is less demand.

The areas of low S' (high population density and high demand) are somewhat offset by the location of the highest revenue areas, focused around industry. In the CCPCUA these high revenue areas are located around population centers, because, other than agriculture, there are few large industries outside of the large population centers. Agricultural users, as intermittent water users, are exempt from the CCPCUA regulation. However, the low weighting assigned to this criteria (C-6) by water professionals, diminishes by the influence of high revenue areas (Appendix B). The Suitability Analysis for the socio-economic factors are the same, regardless of whether the Peedee or Black Creek aquifers are considered, as the socio-economic factors are not dependent aquifer characteristics.

5.4.3. Multi-criteria considerations

When all of the six criteria are integrated into the suitability analysis, the areas that have the highest S' in the Peedee aquifer (Figure 24) lie near the west side of the dewatered area, as defined by the NCDEQ zone map (Figure 31).

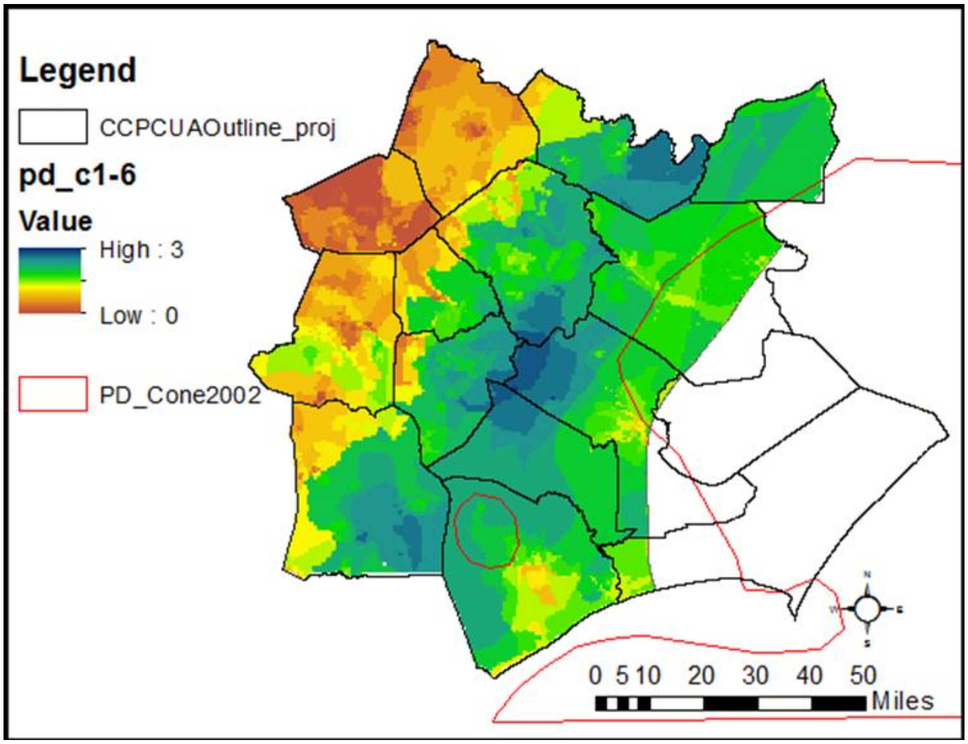

Figure 31. Suitability analysis map showing all characteristics, Peedee aquifer.

The areas at the intersections of Jones, Lenoir, and southern Pitt Counties, and eastern Martin Counties are deemed as suitable areas where pumping strategies can be changed without causing undue burden on the community and/or resource. In contrast, the areas in western Lenoir, and Greene Counties (designated as dewatered regions where maximum reductions have been mandated by NCDEQ), are deemed as less suitable for reductions under the equity framework established in this study. This is likely because aquifer characteristics are less favorable for providing large groundwater yields to the west. The city of Greenville in central Pitt County was also assigned to the dewatered zone by NCDEQ. However, the city has high water demands, and a high population density, making it less suitable for reductions under the equity framework established in this study. Changes to the pumping strategies in Greenville would cause undue burden on the community and/or the resource.

These results compare favorably with the reductions mandated by the CCPCUA for the Peedee aquifer. As shown on Figure 32, both management strategies (suitability analysis and the CCPCUA regulation) roughly agree on the areas for pumping reductions the majority of the area is capable of withstanding.

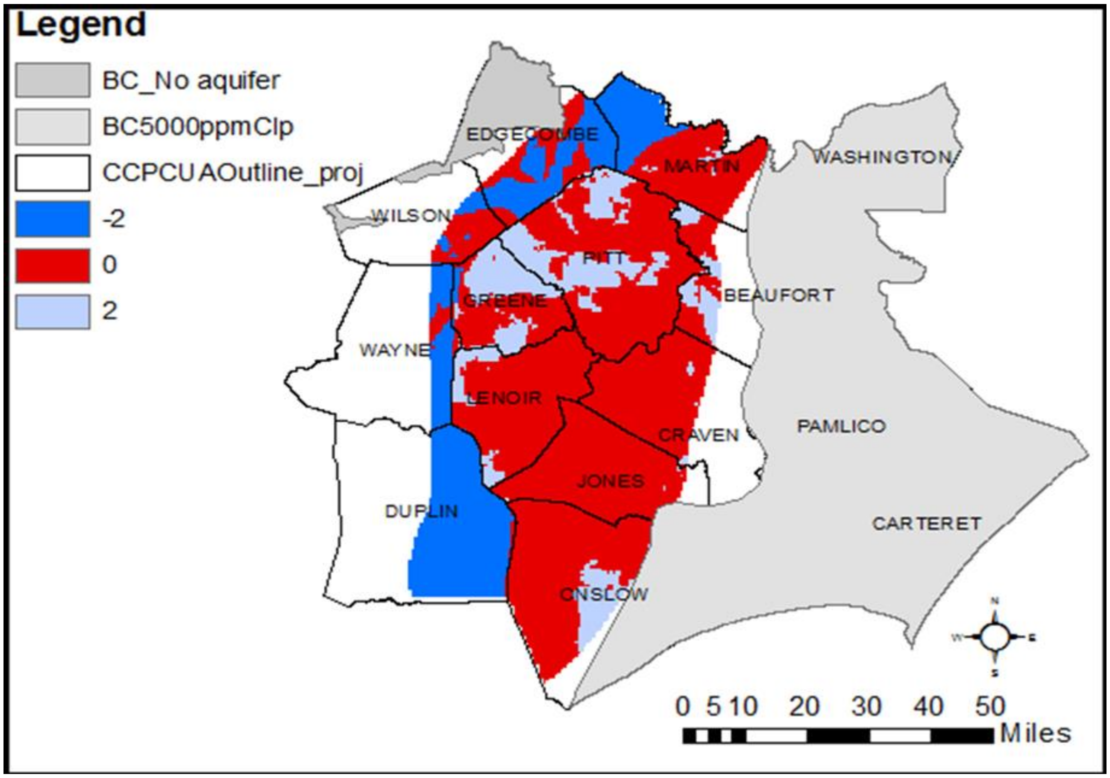

Figure 32. Peedee comparison map, suitability analysis and NCDEQ CCPCUA zone map. Red areas denote agreement between two techniques, light blue denotes areas where the NCDEQ has recommended higher pumping reductions than the suitability analysis, dark blue denotes areas where the NCDEQ has recommended lower pumping reductions than the suitability analysis.

There are some areas however, that do not overlap. The NCDEQ has determined that the west side of Pitt, Greene and Lenoir Counties (shown in light blue in Figure 32) has a higher ability to withstand pumping reductions compared to the ability determined by the suitability analysis.

Much of this area is considered dewatered and is subject to the maximum reductions. This determination was based on the aquifer conditions in 2002. Had the determination been based on a combination of aquifer characteristics and socio-economic conditions, the reductions might not have been as severe because these are areas of low to moderate income and thin, shallow aquifers of low transmissivity (Appendix A). As previously noted, communities in this area have expressed concern about the extent of the reductions.

For the Black Creek aquifer, the least vulnerable areas, according to this study, are also centered at the intersection of Jones, Lenoir, Craven and Pitt Counties, as well as the southeast of Duplin County, the center of Wayne County and the southwest of Martin County (Figure 33). Figure 34 illustrates the difference between the results from the suitability analysis and the map from the NCDEQ showing impaired aquifer conditions. Blue areas denote agreement between two approaches. The red/brown zone represents areas where the NCDEQ has recommended a more rigorous approach to reduce pumping than in areas that were established by the Suitability Analysis. The blue/ purple zones illustrate the areas where the NCDEQ has recommended a less rigorous approach to reduce pumping than in areas that were established by the Suitability Analysis.

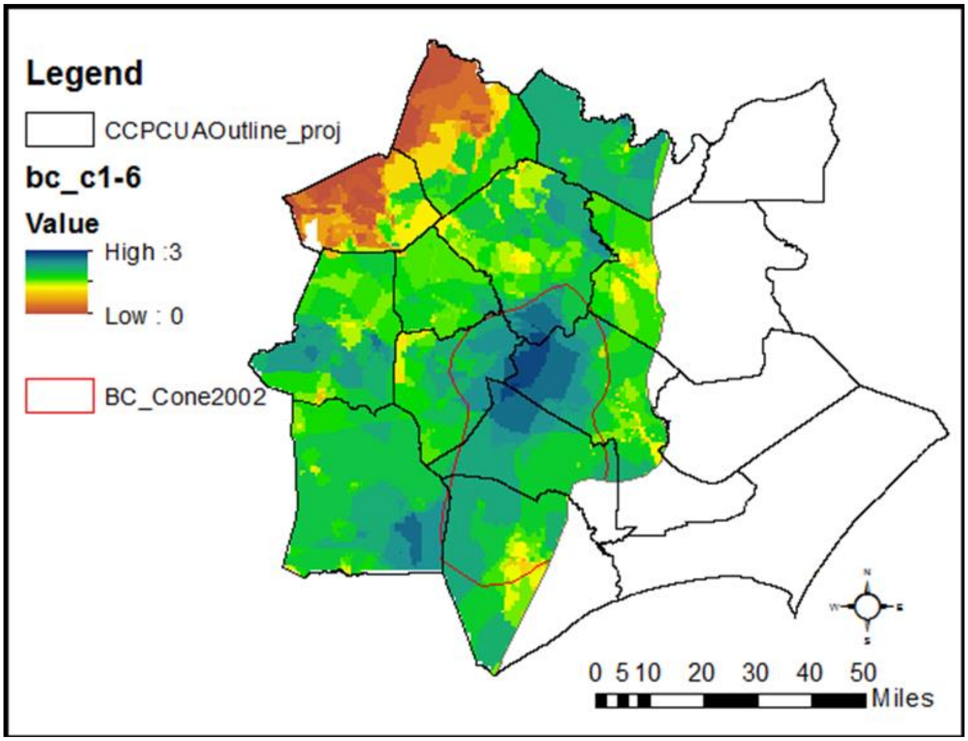

Figure 33. Suitability Analysis Map showing all characteristics, Black Creek aquifer.

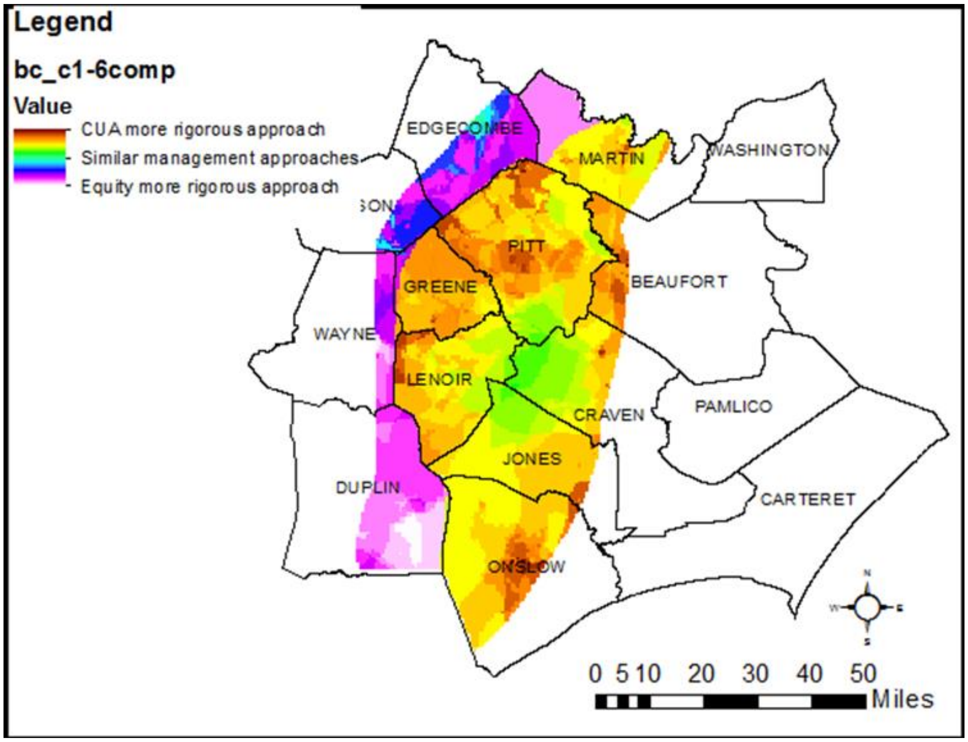

Figure 34. Black Creek comparison map, suitability analysis and NCDEQ CCPCUA zone map. Red areas denote agreement between two techniques, light blue denotes areas where the NCDEQ has recommended higher pumping reductions than the suitability analysis, dark blue denotes areas where the NCDEQ has recommended lower pumping reductions than the suitability analysis.

This research uses the CCPCUA in eastern North Carolina as a case study to compare the outcomes of a management strategy based solely on the aquifer conditions, as assessed by the NCDEQ to one based to an equity. Whereas the first management approach uses aquifer conditions as its measure, the latter simultaneously considers several hydrologic, social and financial criteria.

The original CCPCUA regulation and the Suitability Analyses identify different areas where groundwater withdrawals could be reduced. Whereas, the CCPCUA regulation incorporates one set of management requirements for all of the Cretaceous aquifers, the Suitability Analyses evaluates all aquifers separately, thereby considering the different characteristics and stresses of each aquifer. Although applying different management strategies to different aquifers may be administratively onerous, such an approach is more robust.

Although management strategies have historically been based on aquifer characteristics (e.g., transmissivity or safe yield), the CCPCUA regulation is based on aquifer conditions (e.g., declining, dewatered or saltwater intruded). Salt water intrusion is an aquifer condition that is considered as one aspect of the MCDA process (C-4, available groundwater). The Suitability Analysis strategy, in an effort to incorporate equity, considers social, financial and hydrologic characteristics. These differences highlight the trade-offs between the hydrologic and the socio-economic considerations when developing management strategies. The hydrologic characteristics (transmissivity and safe drawdown) dominate the analyses and highly influence the “all criteria” analyses, as evidenced by the close resemblance of the “all criteria” Suitability Analysis and the “hydrologic characteristics” Suitability Analysis. The analysis that considers the hydrologic characteristics of the aquifer, as well as the integrated hydrologic-socio-economic analysis, both produce results where the areas of low S’ closely match the cone of depression.

It is of note that Greene County successfully lobbied for lower pumping reductions. If the CCPCUA regulation was constructed with a Suitability Analysis tool using equity criteria as suggested in this research, many communities on the west side of the CCPCUA would not have had to fully implement the 75% reductions as mandated by the regulation. Had the 1-3 Suitability Analysis scale been applied to creating the management strategy, each of the three areas might have been managed differently.

5.5. Conclusions

The purpose of any groundwater management tool is to determine how best to protect the water quality and quantity of an aquifer. The approach suggested in this study integrates multi-criteria data while considering different perceptions, scales, inputs and outcomes. The suitability assessment tool identifies areas that benefit from protection. There are important differences between an analysis based on single criteria and the Suitability Analysis, based on multiple criteria. The CCPCUA zone map, as defined by the NCDEQ, established three large management areas. Reductions in groundwater withdrawals were ascribed to each of the three areas based on aquifer conditions and apply to all of the Cretaceous aquifers. Although the reduction areas are generally comparable, as illustrated in Figure 35, the Suitability Analysis map has much finer spatial resolution, therefore defining more precise management areas. The Suitability Analysis displays results for the aquifers individually, as it considers the individual characteristics of each aquifers. This finer resolution provides a tangible rationale for the reductions for each community, based on several, often competing factors. Another advantage to the Suitability Analysis approach is that it is not arbitrary. The reduction areas are systematically and logically assigned through a process that considers different and quantifiable characteristics.

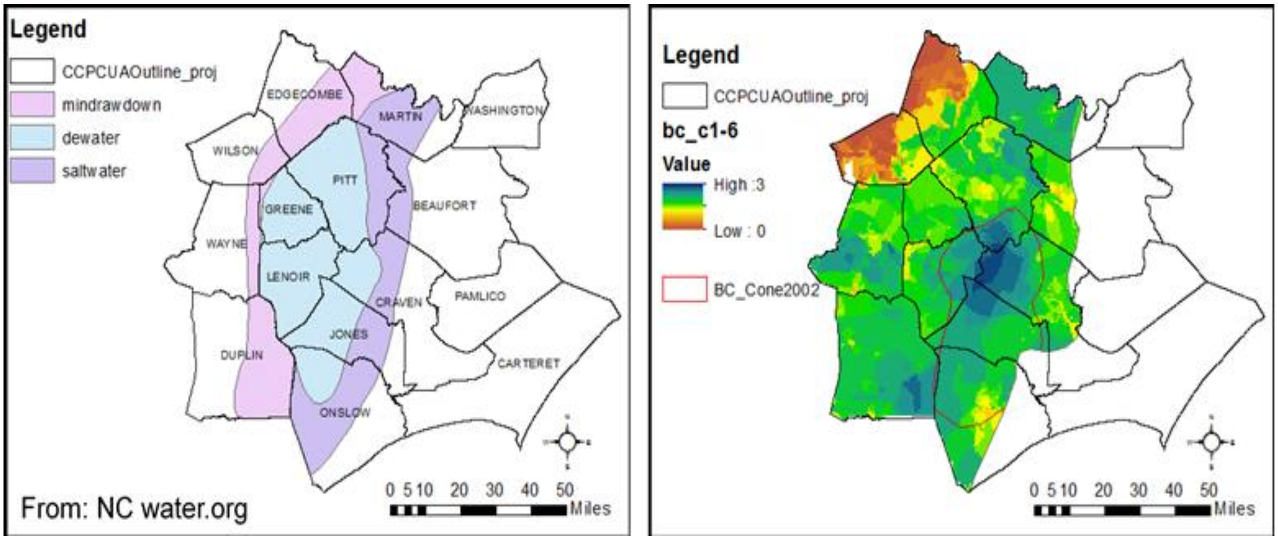

Figure 35. Comparison of (a) three management zones as determined by the CCPCUA regulation (From NCDEQ) and (b) three management areas for the Black Creek aquifer as determined by the Suitability Analysis.

The benefit of a suitability study is that it considers the needs of stakeholder communities, as well as preserves the usable life of the aquifers. While the suitability study of the CCPCUA shows that a large extent of the area is highly vulnerable to changes in pumping strategies, under the CCPCUA regulation, much of the fifteen-county management area is required to reduce pumping by 75%. Fortunately, the CCPCUA provides a mechanism for adjustments to the mandated reductions. However, unless vulnerable communities utilize the option to challenge their reductions and are able to provide justification for those strategy changes, they are susceptible to falling short of providing for and considering the needs and constraints of their communities, as well as causing further damage to the aquifers. A Suitability Analysis based on multiple equitable criteria may be an effective tool to reduce conflict between resource managers and resource users. The study illustrates the utility and power of geospatial techniques combined with MCDA approaches to create effective management strategies which are transparent, defendable and equitable.

6: SUMMARY OF RESEARCH

The research *Suitable Groundwater Management: Equity in the North Carolina Central Coastal Plain, U.S.A.*, focuses on four important processes: 1). Inclusion: giving stakeholders a voice early in the management planning stage, 2). Evolution: appreciating the perspectives of different evaluation and management approaches, 3). Understanding: knowledge of the socio-economic-hydrologic systems, and 4). Integration: crafting integrative evaluation tools.

6.1. Gaps in research/future work

Several gaps came to light during the research which highlight the need for further study. Additional research is recommended in the following sections:

- evaluation techniques
- effective management
- stakeholder engagement.

Although the recommendations are based on gaps identified during the research of the CCPCUA case study, they are applicable to other areas.

6.1.1. Evaluation

A water management suitability analysis serves as the culmination of this research which integrates social, economic, and hydrologic factors. However, predictive models of these interacting systems are difficult, as there are many uncertainties involved with the multiple changing systems. An in-depth social science study of human-water interactions would provide an understanding about the feedbacks between socio-economic and hydrological pressures with better predictions of their actions and reactions. Identifying how the socio-economic and physical systems interact would establish how policy determination and acceptance is affected by changing social norms regarding water. Furthermore, the socio-economic and physical model would define how changing physical conditions alter social norms and perceptions of water use. Because much of the CCPCUA counties are located near or at the coast, any socio-economic-hydrologic study conducted must consider seasonality in water demands.

Transmissivity is vital to understanding the groundwater of the Cretaceous aquifers. Future research might include geophysical techniques to more accurately map the coastal plain aquifers. Time domain electro-magnetic soundings (TDEM's) have been used to identify the salt water fresh water interface (Land, et al., 2004), where apparent resistivity values were derived from the TDEM's. Borehole geophysical logs have been used to determine both transmissivity and hydraulic conductivity of coastal aquifers (Niwas and Singhal, 1985; Lashkaripour and Nakhaei, 2005; Sikandar et al., 2010; Sikandar and Christen, 2012; Singh and Singh, 2016). Utilizing research derived for the oil and gas industry, the studies show correlations between hydraulic conductivity, hence transmissivity and resistivity, and between hydraulic conductivity and the formation factor (f), or the resistivity index (I). Much more accessible than aquifer tests, borehole geophysical logs may be utilized from the existing NCDEQ monitoring network to indirectly determine transmissivity.

In addition to an improved understanding of the spatial distribution of transmissivity, a greater understanding of the spatial deposition and arrangement of the aquifers would greatly improve management of the Cretaceous aquifers. Currently, aquifer characteristics in the CCPCUA are determined through aquifer tests of discrete, individual sand lenses, yet are applied to the entire aquifer interval. Rather than manage each aquifer as continuous, homogeneous and massive permeable, sand unit, mapping individual pulses of sand deposition, bounded by impermeable time markers, would provide a more realistic picture of the aquifer system and aid in the management in these discontinuous, lenticular sand bodies. Mapping individual sands allows for only the analysis of discrete, individual (and connected) sand lenses rather than analysis of the entire aquifer interval. Aquifer characteristics (i.e. T, S, and K) are not indicative of entire interval, but just the tested discrete sand lens.

Groundwater levels are frequently indicators of aquifer health; however, it remains unclear how water level changes relate to changes in storage volumes within the aquifers. Volumetric models of the aquifers provide a more accurate estimate of the relationship between changes in water level changes and changes in storage volumes within the aquifers and clarifies how accurate changes in water levels indicate the overall aquifer health.

The NCDEQ's original design for determining the health of the Cretaceous aquifers included using safe yield as the indicator, with the recharge rate as a proxy for safe yield. However, the NCDEQ deemed the well monitoring network incapable of providing adequate data for a model (Morris, Wilson, personal communication 2008). Prior to the start of the CCPCUA, the NCDEQ did not establish a tangible threshold of recharge as the critical marker for safe yield. The lack of confidence in recharge values is confirmed in Chapter 4, where estimated changes in storage volumes in the Peedee and Black Creek aquifers resulting from pumping are calculated. The expectation is that the change in storage is equal to the difference between the recharge and the withdrawal rates. In fact, this simple relationship does hold to be true. When the recharge exceeds the withdrawal, there is a positive change in storage (a gain of storage volume). However, the values calculated for a loss of storage do not equal the accepted recharge rate minus the documented withdrawals. Definitive values of recharge are still unknown for the Cretaceous aquifers of the Coastal Plain.

The creation of the CCPCUA forms a good basis for regional groundwater planning. However, multi-site evaluations which compare and contrast criteria, issues, and scales between sites will greatly add to the body of learning regarding integrated, multi-criteria assessment tools, and provide a fuller socio-economic hydrologic resource model for coastal plain water systems.

6.1.2. Management

An expanded monitoring well network would provide a more complete understanding of the aquifer system for pre-management analyses, and would be extremely helpful in creating ongoing, adaptive and flexible solutions to create changing visions of the future.

6.1.3. Stakeholder engagement

Stakeholders were included in creating the CCPCUA, however, the stakeholder engagement was limited in scope and diversity, and became involved late in developing the management strategies. Stakeholder engagement is more effective if the preferences of a variety of stakeholders to different water sustainability strategies is determined. This understanding lends greater support for proposed policies. In addition, the decision-making process is more targeted when stakeholder's tolerance of different water sustainability strategies is fully recognized.

6.2 Recommendations

6.2.1. Evaluation

There is no single, desirable formula for evaluating groundwater resources. As the research highlights, evaluation methodologies should evolve and adapt to changing conditions. It is vital that adaptive management strategies keep pace with changing systems. Including integrated socio-economic hydrological investigations combined with spatial analyses provide a clear illustration of the groundwater systems. This multi-dimensional approach accounts for different spatial and temporal scales, and takes into account the interdependence, interactions, and dynamics of the systems. Although the identification of important criteria may vary by locale through time, it is important to incorporate the multi-dimensions, and avoid focusing on independent characteristics (i.e. social, economic, and hydrologic) in isolation. This includes the integration of surficial water bodies and groundwater. Thus, individual water basin planning should be integrated into a larger regional analysis which apply common management frameworks and assimilate all data in common units and/or scales.

Aquifer characteristics (e.g. salt water intrusion) specific to coastal plain regions are complex, variable, dynamic, interacting systems due to the proximity to the land sea interface. These areas experience seasonal demands, needs and financial inputs. Rural communities often surround coastal population centers. Despite the different population distribution, the needs and demands of theses urban and rural communities are different, yet both require available and secure freshwater resources.

6.2.2. Management

As the study of the CCPCUA has highlighted, rigorous groundwater management is the most valuable where the resource is the most vulnerable. A capacity use area where specific areas are closely monitored, and managed, successfully protects “the interests and rights of residents or property owners of such areas or of the public interest (Water Use Act, 1967).” The identification of need, coupled with the establishment of a Capacity Use Area is powerful, and more Capacity Use Areas should be considered where needed, as continued regulations, permitting, and monitoring maintains continuous oversight of the aquifer system.

Whereas, the use of iterative protocol allows for changing short term and long term goals that adapt to changing conditions, backcasting is a valuable instrument that allows policy makers to envision desired future conditions and tailor management to connect the desired future conditions with current conditions.

Ultimately, methods that monitor changing socio-human systems, as well as changing aquifer systems are beneficial. These methods consider the scale and the make-up of the system when determining by whom and how policy is dictated, and who coordinates daily management, and oversight.

6.2.3. Stakeholder engagement

When the necessity to protect resources arises, new and innovative solutions are crucial to promote conservation, inventive water use and reuse, support diversified water use, encourage greater collaboration between social and natural scientists, and foster innovation.

Collaborative efforts which include all stakeholders at an early stage can minimize conflict and maximize cooperation and compliance. By encouraging cooperation between all stakeholders including, interstate agencies, intra-state agencies, public and private utilities, industry, agriculture, environmental, and end users, greater communication between stakeholders and scientists results in acceptable, enforceable solutions. Cooperation includes policy planning, data sharing, facility sharing, and research findings. Greater communication includes building on commonalities; common variables, goals, language, data collection methods and data bases. Communication also involves identifying and communicated to stakeholders a clear chain of decision-making and incorporating greater two-way interactions with elected officials concerning groundwater allocation and management. Cooperation and collaboration merits continued efforts.

6.3. CONCLUSIONS

The central theme of this research is equity with respect to groundwater management. The following conclusions demonstrate how equity affects a wide range of groundwater management problems, both regionally and globally. Although the permitting and compliance and enforcement continue in the CCPCUA indefinitely, the CCPCUA reduction phases expire in July 2019. This may create an opportunity to rethink the regulation based on the research conclusions presented, the new decision support tools and the current conditions of the aquifers. In summary, the following specifically address the research questions outlined in chapter 1.

***Objective 1:* To evaluate the success of the Central Coastal Plain Capacity Use Area regulation.**

***Research Question 1a:* How effective was the application of procedural justice concepts in creating groundwater management policy?**

The application of procedural justice concepts led to stakeholder's involvement in the rulemaking process. Participation in the process gave the stakeholders a feeling of fairness and inclusion. Because they were allowed a voice in the process, they became invested in the rulemaking which increased their trust in the purpose, the process and the outcome of the regulation. Many expressed that their concerns were heard, considered and incorporated into the final rule. As a result, the final regulation was one in which the stakeholders found acceptable and one in which they were willing to comply.

The regulation was acceptable to both the conveners and the stakeholders and, as a result was enforceable. The ability to enforce reduced pumping rates and mandatory permits resulted in the improved sustainability of the aquifers. Water levels recovered, the cones of depression reduced in aerial extent, and chloride concentrations declined. In addition, the development of conservation measures, alternate water sources and conjunctive water uses decreased pumping from the Cretaceous aquifers and increased the continued security of the water supply.

***Research Question 1b:* How did stakeholder participation in the rulemaking process result in groundwater management policy and changes to groundwater characteristics?**

Rapidly declining water levels, salt water influx, low well yields and land subsidence are valid reasons to construct a regulatory tool to manage the water resources of Eastern North Carolina. Few denied the existence of a problem, however, there was much disagreement for the best solution. Prior to including stakeholders in the rulemaking process, the state proposed regulations based on scientific information provided by resource advisors and water level data collected by the state agency. These initial proposals were viewed as burdensome, “unfunded mandates” which lacked public input.

Although well intentioned, the initial proposals were met with opposition. Stakeholders did not understand the decision-making process and perceived the unilateral approach by the state agency as unfair and exclusive. This left the stakeholders feeling powerless and vulnerable to the demands of a seemingly biased authority, which showed no regard for their needs. Having the ability to voice their concerns and participate in the outcome increased the stakeholder’s trust and acceptance of the state agency and the proposed regulation.

The process of crafting the Central Coastal Plain Capacity Plain Use Area regulation ended as a successful story of collaborative procedural justice. After several aborted attempts to obtain community support, DWR realized the importance of following fair and equitable procedures to resolve the conflict. The final rule successfully satisfied the needs of the regulators to protect the integrity of the Cretaceous aquifer and the interests of a diverse stakeholders group. The interviewed stakeholders, represented on the rule making committee, expressed a clear understanding of how and why the regulation was developed. They succeeded in enacting a regulation based on their input, while providing predictability for future planning purposes. The conveners succeeded in enacting a regulation that reversed the declining water levels and initiated conservation measures. Conversely, the stakeholder groups excluded from the rulemaking process viewed it as unfair and were dissatisfied with the outcome. This validates the importance of stakeholder participation. Procedural research theory also confirms this reaction, as process appears to be more valued than outcome, and frequently independent of the outcome (Rohl & Machura, 1997). In the end, the use of procedural justice created a fair, powerful, adaptable and enforceable rule with which the stakeholders were willing to comply. As stated by John Morris, the director of the North Carolina Division of Water Resources, "The administrative rule responds to the desire of water users to have a predictable and fair schedule for moving toward a sustainable water supply (J. Morris, personal communication, 2000)."

Objective 2: **To evaluate alternate groundwater management approaches that incorporate physical and social aspects for equitable groundwater allocation.**

Research Question 2a: **How have groundwater management theories evolved from safe yield to an equity based measure?**

Early references to groundwater management focused on safe yield. Safe yield, as originally conceived, focused on simple water balance equations, where withdrawals were maintained to equal recharge. This traditional approach neglects the diverse environmental, economic, and social demands on the hydrologic system.

The literature includes examples of how groundwater management approaches have evolved from safe yield to sustainability and resilience; each refinement includes additional dimensions involved with managing the groundwater system. Sustainability includes the concept of time, suggesting the need to consider current and future needs. Resilience considers the ability of the aquifer to adapt to and recover from physical, social and economic changes. The inclusion of equity in the groundwater management dialogue considers the coupled and changing physical, social and economic demands as an integral part of the hydrological cycle.

Research Question 2b: To what extent did the 75% reductions mandated by the Central Coastal Plain Capacity Use Area regulation consider equity?

The outcomes of the suitability analyses compare favorably with the 75% reductions mandated by the CCPCUA regulation. Although the regulation did not include the multi-dimensions involved with equitable groundwater management, the areas deemed capable of withstanding changes in pumping strategies are similar.

The 2002 CCPCUA regulation was enacted to protect the sustainability of the Cretaceous aquifers. The regulation was successful in reversing the trend of declining water levels, however, it was not easily developed by regulators, nor was it enthusiastically embraced by stakeholders. It is the conclusion of this research that inclusion of equity at both the analysis and the development stages would have fostered transparency, accountability, and stakeholder investment in common goals, thereby reducing potential conflicts. The integrated equity framework developed through this research presents a new solution for avoiding conflict, while proposing a decision support tool for creating sustainable aquifers, economies, and societies. This approach suggests a viable alternative to support decisions which sustainably manage aquifers, while providing for stakeholder’s basic needs for water security, inclusion, and respect.

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APPENDIX A: CRITERIA

Criteria is a standard on which judgment or decision may be based (*Merriam-Webster's collegiate dictionary*, 2003). Groundwater management criteria impact groundwater sustainability and use. Although not an exclusive list, the following six criteria chosen for this research are adapted from international guidelines on water resources, the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (United Nations, 1997) and the subsequent modifications, the Berlin Rules (ILA, 2004). The criteria are: 1) hydrogeologic characteristics, 2) demand, 3) population, 4) available groundwater, 5) availability of alternate water sources, and 6) financial ability to fund alternate water sources.

A.1. Methodology

This study adapts the criteria suggested by the UN (1997) to meet the goals of this research. Each criteria layer illustrates the spatial distribution of the individual criteria data displayed using ArcMap 10.4.1. Through reclassification, each layer is assigned values of 1, 2 or 3, with 1 representing the areas considered the citizens would be the most vulnerable to changes in pumping, and 3 as the areas where the citizens would be the least vulnerable to changes in pumping. All GIS layers appear in NAD 1983, State Plane, North Carolina, FIPS 3200 meters coordinate system. The GIS analysis is limited to the fifteen CCPCUA counties. The first (33%), second (66%) and third (99%) quantiles define the reclassified quantitative data.

A.1.1. C-1 Hydrology

The two aquifer characteristics deemed the most important by this researcher are transmissivity and safe drawdown, with both characteristics being equally influential. Therefore, transmissivity and safe drawdown are both assessed equal weights in the final analysis.

Transmissivity

Transmissivity values, derived from aquifer tests performed on both observation and pumping wells, are a part of the statewide regional monitoring network and are available from the North Carolina Department of Environmental Quality, Water Resources Division website (ncwater.org). Hydraulic characteristics are calculated using either the Theis time-drawdown, the Jacob time-drawdown or the Hantusch-Jacob time-drawdown methods.

The interpolated, contoured, and clipped ArcGIS thematic layers illustrate the transmissivity trends for each aquifer within the CCPCUA. The aquifer test wells which provide transmissivity data points for the Peedee (n= 37) and the Black Creek (n=35) aquifers are poorly distributed and sparsely located within the CCPCUA. The majority of the Peedee aquifer tests were performed in Brunswick and New Hanover counties, whereas, the Black Creek aquifer tests were highly clustered in Onslow County. Due to this paucity of data, transmissivity trends are difficult to map. The convention dictates that transmissivity values increase with increasing aquifer thickness (personal communication R. Spruill). Individual, discontinuous sandy intervals within each aquifer typically yield the most water and are those which are tested for transmissivity. Therefore, to support the assumption of increasing transmissivity with increasing aquifer thickness and thereby substantiate the mapped transmissivity trends, the relationship of net sand present within the gross aquifer interval to transmissivity is examined using available geophysical logs. The net sand is the vertical distance encompassing the gamma ray deflection from a shale baseline. The gross interval is the vertical difference between the top of the aquifer and the top of the next (deeper) confining unit. By counting the vertical distance encompassing the gamma ray deflection from a shale baseline, an estimate of the net sand in each aquifer is calculated (Figure 36). Where no gamma ray logs are available, the sand count is determined from the spontaneous potential log using the same method of deflection from a shale baseline (Figure 37). For each aquifer, plots demonstrate the degree of correlation between transmissivity, aquifer sand content and aquifer thickness. In addition, because transmissivity is equal to the aquifer thickness multiplied by the hydraulic conductivity, a plot of hydraulic conductivity versus transmissivity displays the level of correlation between the two variables.

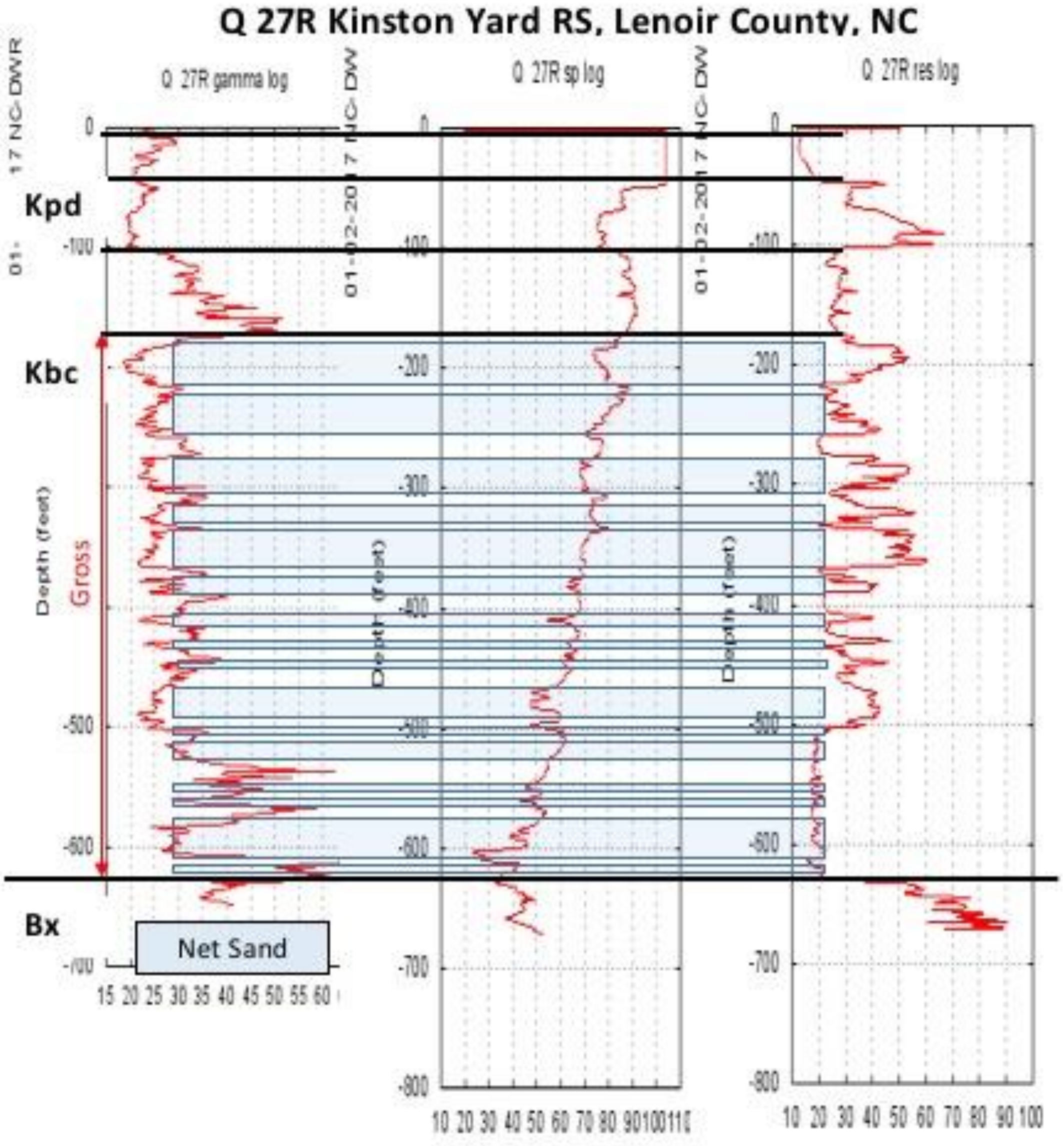

Figure 36. Example of determination of net and gross sand from spontaneous potential and resistivity logs. An indirect measure of transmissivity.

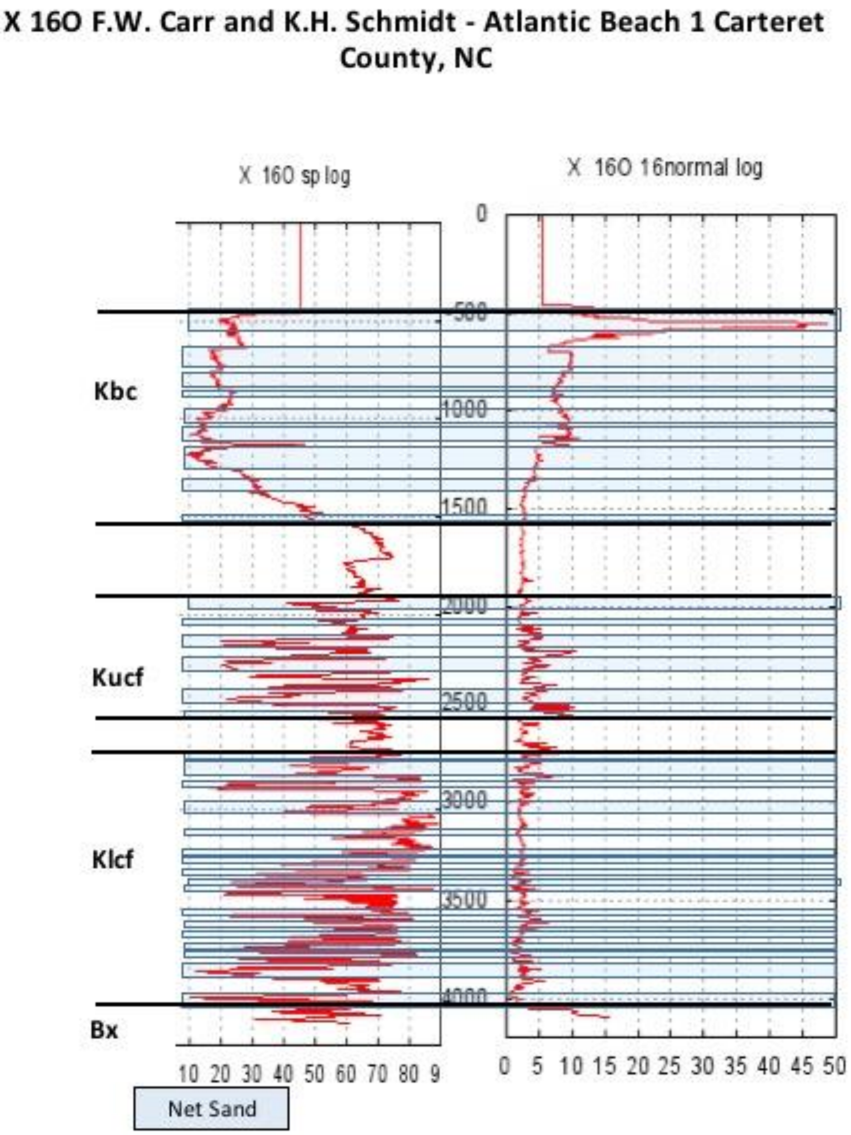

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Figure 37. Example of determination of net and gross sand from spontaneous potential and resistivity logs. An indirect measure of transmissivity.

Once verification of the mapped transmissivity trends occurs, the transmissivities for each aquifer is reclassified into three value categories from one to three. For the Peedee the following transmissivity assignments, based on quantiles, are:

- One (1), low transmissivity values (0-553 ft^2/d)
- Two (2), medium transmissivity values (554-1150 ft^2/d)
- Three (3), high transmissivity values (>1,151 ft^2/d)

For the Black Creek the following transmissivity assignments are:

- One (1), low transmissivity values (0-672 ft^2/d)
- Two (2), medium transmissivity values (673-1,153 ft^2/d)
- Three (3), high transmissivity values (>1,154 ft^2/d)

Safe drawdown

Safe drawdown reflects the vertical distance between the elevation of the top of each aquifer and the original pre-pumping potentiometric surface elevation for that aquifer. The tops and base of the aquifers are obtained from the North Carolina Department of Environmental Quality (NCDEQ), Division of Water Resources website (ncwater.org), as well as from the files of a private hydrogeologic and engineering consulting firm. ArcGIS map layers display the aquifer tops, and the pre-pumping values, estimated from near the turn of the twentieth century (Geise et al., 1997). Rather than calculate the safe drawdown at discrete well locations, the ArcMap raster calculator computes the differences between the two raster surfaces to create the safe drawdown surfaces for the Peedee and the Black Creek aquifers throughout the area. This is a more complete representation of the safe drawdown for the area. Construction of the safe drawdown thematic layers for the aquifers are similar to the methodology used for the transmissivity analysis, as they are contoured and then reclassified into three zones. The classes, or zones for the Peedee aquifer are:

- Zone One (1), low safe drawdown (0-108 feet)
- Zone Two (2), medium safe drawdown (109-660 feet)
- Zone Three (3), high safe drawdown (>660 feet)

The Black Creek aquifer reclassifications are:

- Zone One (1), low safe drawdown (0-309 feet)

- Zone Two (2), medium safe drawdown (310-860 feet)
- Zone Three (3), high safe drawdown (>860 feet)

A.1.2. C-2 Demands

For this research, the terms “demand” and “need” are synonymous; the assumption is that the CCPCUA water purveyors meet 100% of the needs of the communities. Values for the daily demand data are sourced from local purveyor water supply plans, filed with NCDEQ. The demand data used in the analysis reflect the total water (surface, ground and purchase) delivered to the respective community by a service provider for the year 2002. This does not include water obtained by individuals from private wells or other, non-community-based sources. The areas that have the highest demand are deemed the most impacted by changes in pumping. The demand data are reclassification into three classes according to percentiles as follows:

- Zone One (1), high demand (>0.510 million gallons per day).
- Zone Two (2), medium demand (0.147 – 0.510 million gallons per day)
- Zone Three (3), low demand (0-0.146 million gallons per day)

The reclassified values are plotted on an ArcGIS map within the service provider outlines which are provided by the NC Center for Geographic Information and Analysis (NCGIA) GIS dataset. All outlines represent the service provider areas for the year 2003 except for Fort Bragg and Marine Corps Base Camp Lejeune. These military bases did not provide an outline of their area. Due to this omission, the boundaries used for their provider area mimic the outline of the bases. The analysis omits current permit holders who did not hold permits in 2002, or who were not included in the NC Center for Geographic Information and Analysis (NCGIA) GIS dataset. Also omitted are private industries, universities, water impoundments and golf courses for whom there is no service provider outline.

A.1.3. C-3 Population

Data on the block group level represents the smallest geographical representation of the population available from the 2000 U.S. Census Bureau from which information is obtainable. Because the block group contains up to 1300 citizens, the block group size varies widely. Typically, rural communities encompass larger areas and highly populated areas encompass small areas. Therefore, to obtain a better spatial representation of how the citizens are distributed throughout the area, the population count is normalized by the block group size and displayed as population density. The highest population density areas are the most vulnerable to changes in pumping and therefore reassigned to the lowest zone (1).

- Zone One (1), high population densities (7,527-174,471 people/square mile).
- Zone Two (2), medium population densities (1,079 – 7,526 people/square mile)
- Zone Three (3), low population densities (0- 1,078 people/square mile)

A.1.4. C-4 Available groundwater

Thematic layers for criteria four demonstrate the availability of potable Peedee and Black Creek groundwater in the CCPCUA at of the start of the regulation. Each aquifer map displays four zones, representing a ranking of importance. The zones are as follows:

- Zone Zero (0), unusable or non-existent aquifer
- Zone One (1), limited aquifer thickness
- Zone Two (2), salinity transition zone
- Zone Three (3), full aquifer thickness, potable water needing a minimum of treatment

In order of increasing importance, zone zero, is an area within the CCPCUA where no aquifer exists, as it has outcropped and been eroded. This ranking has no value. Zone 0 also includes the dewatered area and the area within the aquifer where the chloride readings are greater than 5,000 ppm. This portion of the aquifer has poor quality water and, in 2002, was not economically viable for reverse or forward osmosis processes. Zone 1 has good quality water, but has an incomplete aquifer thickness, as it truncates at the outcrop. The groundwater within this zone is potable with minimal treatment. Zone 2 is the chloride transition zone. Chloride measurements within this zone measure between 250-5,000 ppm. The most suitable zone for reductions has the assignment of zone 3. The aquifer in this zone has the full aquifer thickness with chloride values below 250 ppm.

Aquifer tops and bottoms, obtained from the North Carolina Department of Environmental Quality (NCDEQ), Division of Water Resources website (ncwater.org) as well as from the files of a private hydrogeologic and engineering consulting firm, are the basis for the zone maps. To determine the outcrop of the top and base of each aquifer, the ArcGIS raster calculator subtracts the top and bottom of each aquifer surface (Figures 38-41) from a digital elevation model (DEM) of the ground obtained from NC One Map. A difference of zero indicates the intersection of the DEM and the top or bottom aquifer surface, displaying the line of outcrop for top or base of the aquifer. The DEM contains 2’ contour intervals and 20’ grid cells. Areas west of the outcrop of the aquifer base, is assigned a zero. The area between the outcrop of the top and the base of the aquifer represents an incomplete section and is assigned a 2.

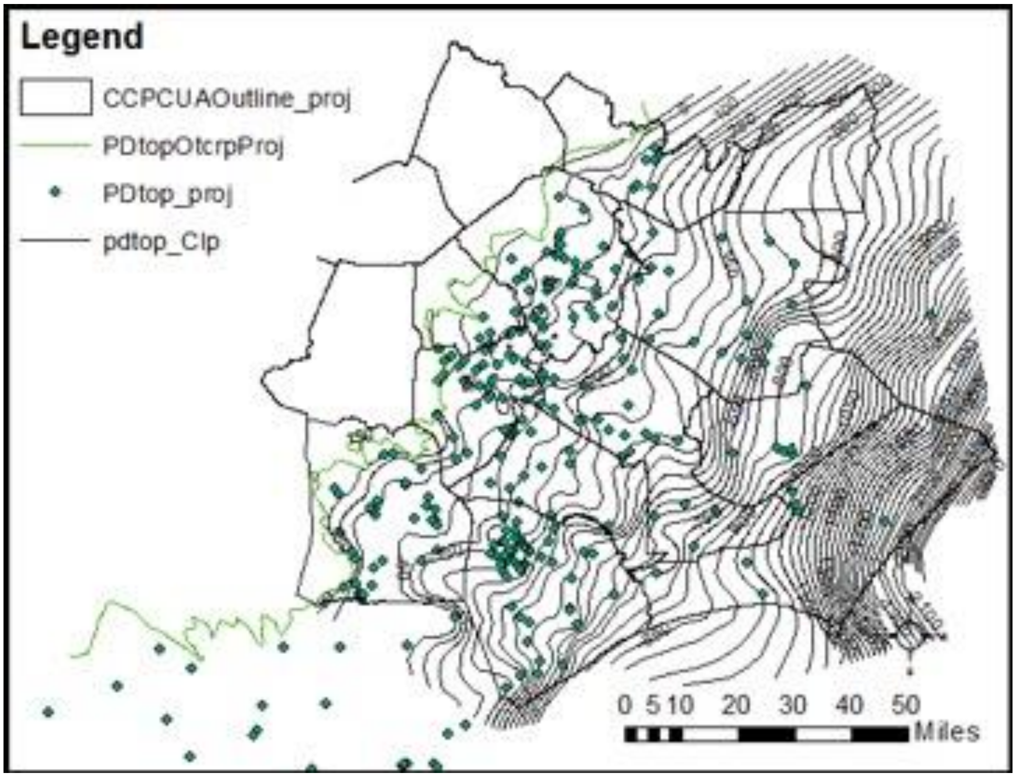

Figure 38. Structure map top Peedee aquifer. C.I.=50’.

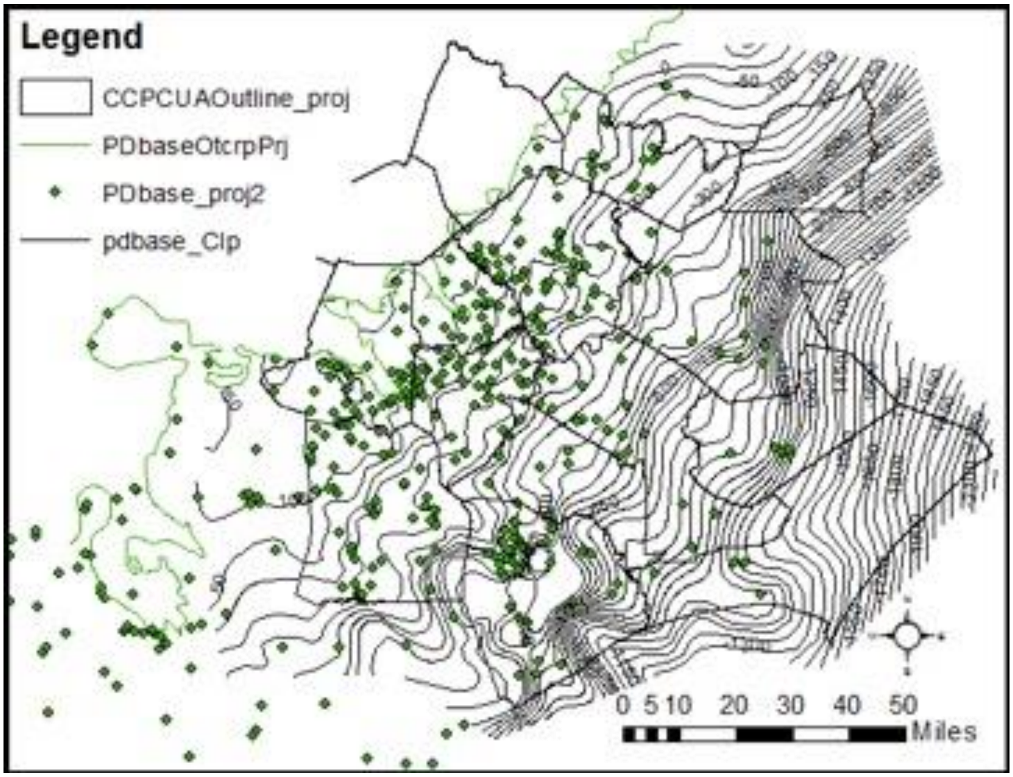

Figure 39. Structure map base Peedee aquifer. C.I.=50'.

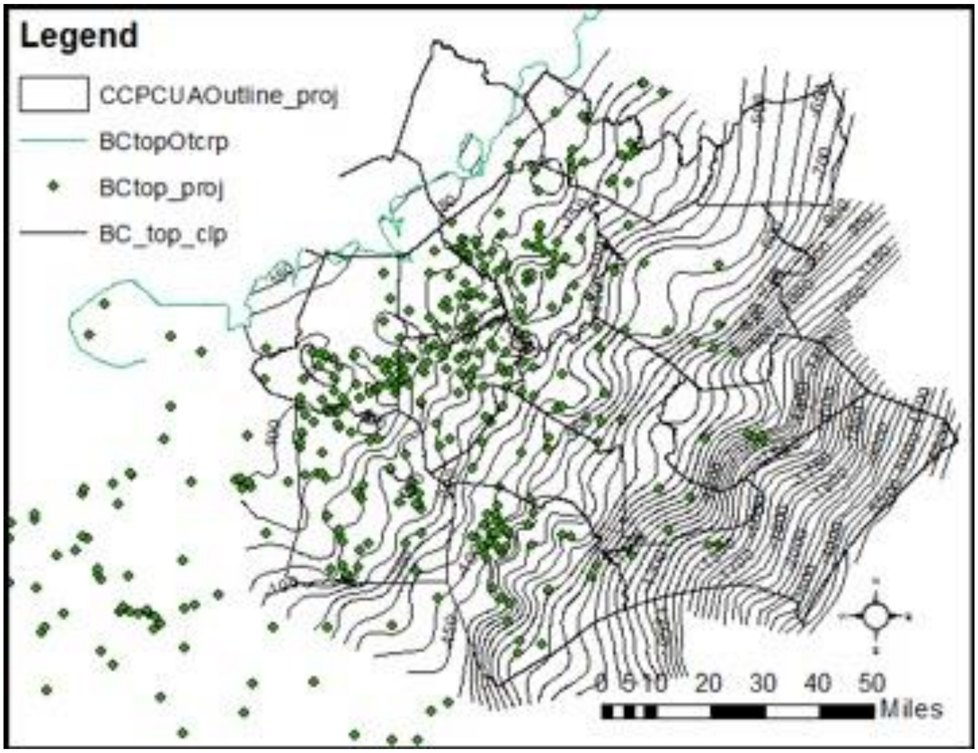

Figure 40. Structure map top Black Creek aquifer. C.I. =50’.

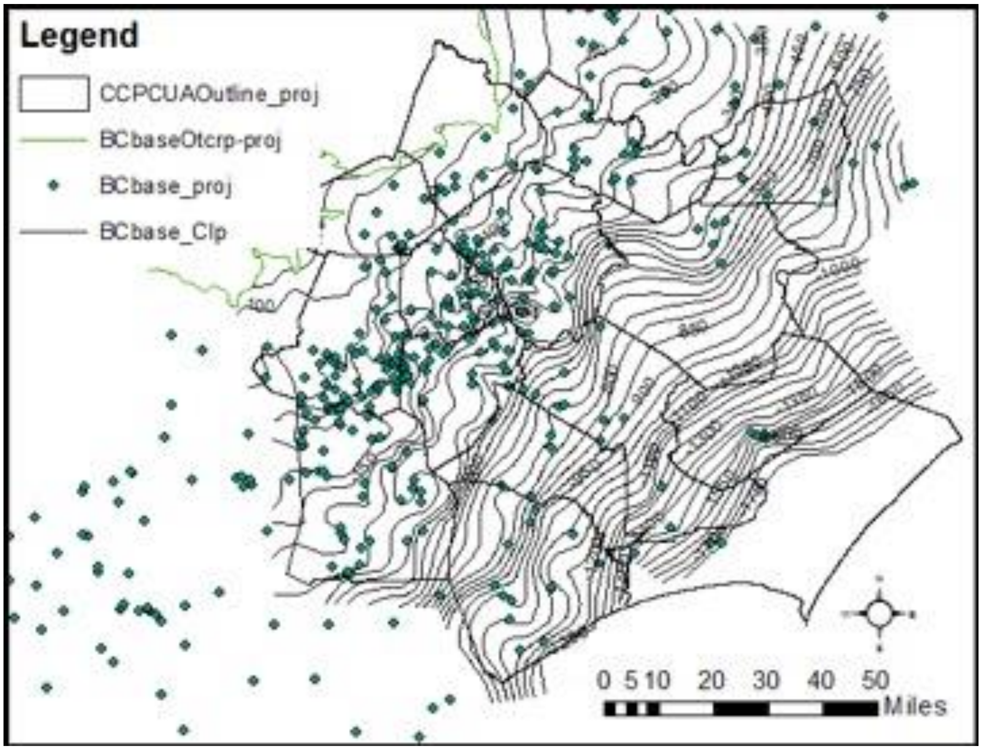

Figure 41. Structure map base Black Creek aquifer. C.I.= 50'.

Plotted, interpolated and contoured chloride values, also obtained from the NCDEQ and the private hydrogeologic and engineering consulting firm, create the outlines for the transitional chloride zone (250-5,000 ppm) and the high salinity zone (> 5,000 ppm chloride). The area between the transitional zone on the east and the limited section on the west has a full, high quality aquifer section and assigned the maximum value of 3.

A.1.5. C-5 Alternate water source, surface water

Alternate water sources, when available, are important in meeting the water demands for a community. Criteria 5 investigates the availability of surface water sources for each purveyor unit within the CCPCUA. A merged, single map displays the independent analysis of the five river basins. Each basin has been evaluated separately to avoid the influence of data from adjacent basins. The map uses 7-day, 10-year low flow (7Q10) values compiled by the USGS streamstats database (Weaver, et. al. 2016), 12-digit hydrologic derived river basins shapefiles and major hydrography data from the NC Onemap Geospatial portal.

Thirty-six gage stations, provided in the USGS report, measure flow data within the five HUC drainage basins (Figure 42). Because the USGS calculates 7Q10 values for stream or river segments that are unaffected by wind or lunar tidal influence, no values are calculated for the gage site of the Greenville Utilities (GUC) water treatment plant on the Tar River at Greenville or the Martin County Regional Water and Sewer Authority (MCRWASA) on the Roanoke River in Williamston. These two additional locations are added to the shapefile with the value assigned the GUC gage at an existing gage on the Tar River in Greenville, and the intake location for the MCRWASA in Moratoc Park sited as the intake location. No gages were available in the White Oak River Basin. By law, water treatment plants may withdraw 20% of the 7Q10 value. Therefore, to add these additional data points, a calculation of 7Q10 values relies on the maximum allowable water volume permitted for treatment at the plants. Assuming the 22.5 million gallons of water per day (mgpd) currently permitted for the GUC plant is 20% of the 7Q10, the assigned 7Q10 for the GUC location calculates as 112.5 mgpd (174 cfs). For the MCRWASA, assuming the maximum allowable amount permitted (2.0 mgdpd) is 20% of the 7Q10, the assigned 7Q10 for the MCRWASA location is 1.34 mgpd (15 cfs).

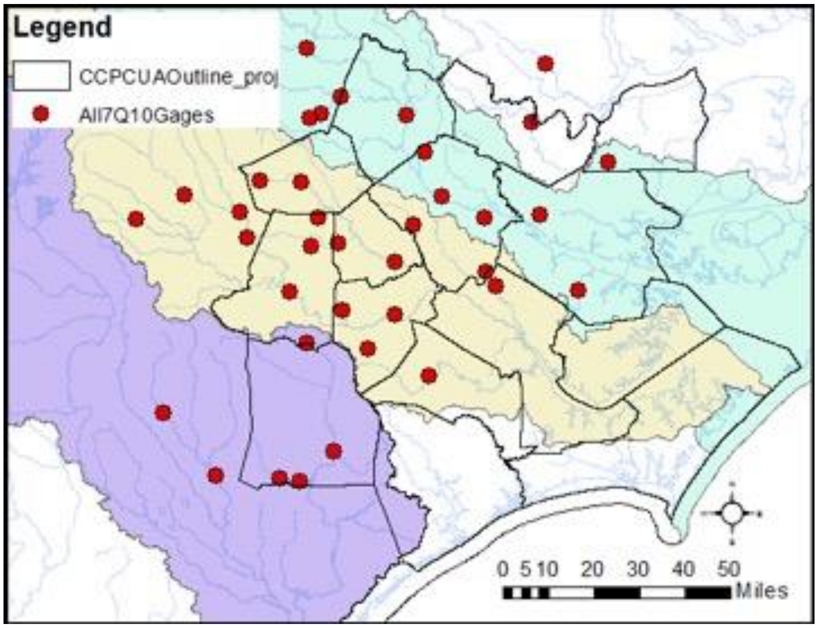

Figure 42. Thirty-six gage stations within the 5 HUC drainage basins.

Shapefiles from the NC Onemap Geospatial portal illustrate HUC river drainage basins and major hydrography. The map displays the major rivers and tributaries, as well as gages, with their respective 7Q10. A separate shapefile of additional points adds the headwaters of each tributary. These headwater positions designate 7Q10 values of zero, as the headwaters are the highest points which contribute to the flow. Merging the tributary shapefile with the gage shapefile creates a raster surface from the gage points. Interpolation, using the two-dimensional minimum curvature spline technique, creates a contoured surface that goes through each input gaged point and represents lines of equal 7Q10 values (isoline). Geometric intersections of the isolines with the surface water bodies creates new 7Q10 data values along the surface water bodies between the measured gages, thereby increasing the density of data points. Thiessen polygons created around each of the measured and interpolated points define areas of influence. Bisecting lines, perpendicular to a line connecting all adjacent points, create the Thiessen polygons. The intersection of each bisecting line defines the vertices of each of the Thiessen polygons.

Each Thiessen polygon represents a single 7Q10 value, either measured or interpolated. Following Tobler's First Law of Geography, "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970), everything within a Thiessen polygon closely relates to the interpolated or measured point within that polygon. The polygons are then color coded and indicate areas of no (0 - 0.001 cfs), low (0.002 - 150 cfs), medium (150.001 - 250 cfs) and high (>250.001 cfs) availability of surface water based on actual and interpolated 7Q10 values.

A.1.6. C-6 Financial capability

When there is a reduction in the primary source of water for communities, their needs must be met through other sources. Shifting from established aquifers to alternate water sources is economically costly, and ultimately borne by the consumers. Although it is the responsibility of the water providers to find solutions to the reduced ability to withdraw from the aquifers, the financial burden falls to tax payers in the form of increased tax obligations. This analysis assumes that loans and grants are not sources of funding.

The financial ability to develop alternate water sources is determined by the hypothetical change in taxes to the end users resulting from the loss of groundwater volumes through reductions required by the CCPCUA regulation. The protocol includes evaluating four alternate replacement water sources: new groundwater, new surface water (including active quarries and quarry lakes), saline water, and bottled water. The analysis begins by exploring the existing tax base. Total employment numbers, by county, are obtained from the 2000 United States Census (US census) on the block group level (*https://factfinder.census.gov*) and mapped in a GIS environment. The 2000 census represents the most accurate employment numbers at the time of the inception of the CCPCUA in 2002. The total employment includes imputed data (data of the labor force added to compensate for missing data, but not actually counted). The labor force is a proxy for the number of taxpayers. Using the 6% North Carolina tax levied in 2000 (https://taxfoundation.org/), the average taxes collected per block group is calculated by multiplying the average income per block group by 0.06.

Spatial units based on customer service areas provide the basis for all calculations for the financial analysis. Each service area differs in aerial extent and in number of consumers served. The individual service provider's units are sourced from a GIS data set created by the North Carolina Center for Geographic Information and Analysis (NCCGIA). The "Type A Current Public Water Systems" data set contains information for the year 2003 and provides information such as size, water use, water treatment and needs of each water system in North Carolina.

The spatial boundaries of the water providers do not correspond with the block group census boundaries; therefore, an aerial weighted interpolation technique determines the proportion of the value of taxes for each provider unit within the CCPCUA. By first calculating the area of each block group within the CCPCUA, the ArcMap union tool is used to combine the different water provider units, essentially creating new units from the old, where new tax liabilities for each of the provider units are apportioned. Dissolving and combining the new features based on water provider's area proportionally assigns the taxes paid per person in 2000 to each provider unit.

The CCPCUA regulation stipulates that each provider located within one of the three defined CCPCUA aquifer zones (declining water levels, dewatered or transitional zone) pumping more than 100,000 gallons of water per day, from the Cretaceous aquifers, must reduce their pumping by 30 – 75% from a predetermined approved base rate and aquifer conditions at the start of the CCPCUA. Because the demand has not decreased, alternative water sources must replace the reduced water volumes. The financial analysis is based on the replacement value of these mandated pumping reductions and is calculated from the approved base rates (ABR) gathered from NCDEQ, Division of Water Resources permit holder information, online (ncwater.org). The calculated, mandated reduced water volumes for each permit holder assumes a total maximum reduction of either 30% or 75%, over the lifetime of the CCPCUA regulation, contingent on where each permit was located. As mandated by the CCPCUA regulation, aquifer zones with declining water levels were required to reduce pumping rates by 30% over 3 phases and wells experiencing salt water encroachment or dewatering were required to reduce pumping rates by 75% over the three phases. Superimposing the ArcMap shapefile of each permit holder over the aquifer zone map determines the appropriate reductions (0%, 30%, 75%) for each permit holder starting at the completion of phase 1 in 2008 and running through the end of 2018. The volume of reduced water is calculated over an eleven-year period, through 2018. Although pumping volumes do not suddenly change, to calculate reduced volumes, pumping for each phase holds constant and changes only at the beginning of each subsequent phase (2013 and 2018).

Engineering firms, personal communications and publicly available online data provide estimates for fixed capital, and variable operational and maintenance costs to develop the alternatives (new ground, surface, saline, and bottled water). Costs for new groundwater sources involve the drilling of a new well field to use undeveloped or underused aquifers, such as the Peedee aquifer. New surface water sources include the construction costs of a new surface water intake and a water treatment plant. The use of saline ground water (1,000 - 5,000 mg/L) necessitates costs for the construction of a reverse osmosis (RO) or forward osmosis (FO) plant. There is no consideration of environmental or social costs in the analysis.

Each of these three options requires upfront capital costs and ongoing operational and maintenance costs (O and M). The final option, the use of bottled water, requires no upfront capital investments, only the annual cost to purchase packaged water, therefore the bottled water option only considers O and M costs. Using the United States Department of Labor, Bureau of Labor Statistics consumer price index inflation calculator adjusts all values to the year 2002. O and M costs also adjust to account for the time value of money. The net present value of the investments in alternate water sources is adjusted using a nominal rate of 4.875% (USDA, NRCS 2017) and is calculated in excel using the equation 1.

Net present value of the investments =

$$\frac{Annual\ Net\ Cost\ base\ year}{(1+discount\ rate)^{\ years\ since\ inception}}+\frac{Annual\ Net\ Cost\ year\ 2}{(1+discount\ rate)^{\ years\ since\ inception}}+\cdots+\frac{Annual\ Net\ Cost\ final\ year}{(1+discount\ rate)^{\ total\ years\ since\ inception}}$$

(Eq. 2)

Supply and demand are held constant. The calculations start in the year 2008, and continued until 2018, the end of the CCPCUA mandated reductions. Inflation for O and M costs adjust for future years using the United States Department of Labor, Bureau of Labor Statistics, consumer price index inflation calculator. The cost estimates provided are for various facility sizes and are normalized to a facility of 5 million gallons of water per day capacity. This method appears valid, as several of the cost estimates provided by engineering firms were given on a gallon per day basis.

Assuming each provider funds individual projects, the financial indicator of an area's ability to fund alternate water source projects is the percent change to each taxpayer's burden, obtained by multiplying the replaced number of gallons by the cost of the alternative water source, calculated by provider area. Because the cost estimates represent a capacity of 5 million gallons per day, the cost for each provider is reduced or increased proportionally to the needs of each service area and is spread out over the 11 years reduction period. Equation 2 shows the overall cost calculation for each service provider area. Because the cost estimates vary, sensitivity analysis was conducted using the range of costs. Mean costs are used to create the financial analysis ArcGIS layer.

Overall costs =

$$\frac{Volume\ of\ water\ reduced, g}{(5MMgpd * 11\ years * 365\ days)} * \ Cost\ of\ Alternative$$

(Eq. 3)

The volume of water reduced for each water provider, measured in gallons, represents the total volume of water reduced over the 11-year analysis period. Equation 3 calculates the total cost to each taxpayer for each of the four alternatives within each service provider area. This is the total cost to the providers per year over the 11-year time period investigated.

Total cost to each taxpayer within each provider unit =

$$\frac{Cost\ of\ Alternative\ to\ provider\ unit}{taxpayer\ population\ within\ the\ providers\ area}$$

(Eq. 4)

The percent increase in the taxpayer burden is calculated using equation 4.

Percent increase in the taxpayer burden within each provider unit =

$$\frac{Total\ cost\ to\ each\ taxpayeprovider\ unit}{Original\ taxpayer\ burden} r\ within\ each \quad *100$$

(Eq. 5)

A.2. Results

A.2.1. C-1 Hydrology

Transmissivity for the Peedee aquifer ranges from 42 to 15,516 ft^2/day, with a mean of 2,325 ft^2/day, a median of 777 ft^2/day and a mode of 656 ft^2/day (Table 5). Due to limited data, it is difficult to distinguish a definitive transmissivity trend, however, following the convention of transmissivity increasing with increasing aquifer thickness, the contour map of transmissivities (Figure 43) increases to the east, following the thickening trend of the Peedee aquifer to the east (Figure 44). The plot of net sand to gross Peedee interval versus transmissivity (Figure 45) tenuously supports this convention, as does the plot of net sand versus transmissivity (Figure 46); there appears to be a trend of increasing transmissivity with increasing quantity of sand in the overall interval. However, the plot of gross aquifer interval to transmissivity (Figure 47) does not confirm this assumption and illustrates no association of transmissivity with gross aquifer interval. The data, however, is inconclusive. The analyses show no correlation between hydraulic conductivity and transmissivity (Figure 48).

(a)

range	42-15516
mean	2325
median	777
mode	656

(b)

Range	289-2,941
Mean	1,019
Median	911
Mode	481

Table 9. Basic statistics for transmissivity, (a) Peedee aquifer, (b) Black Creek aquifer, ft^2/d.

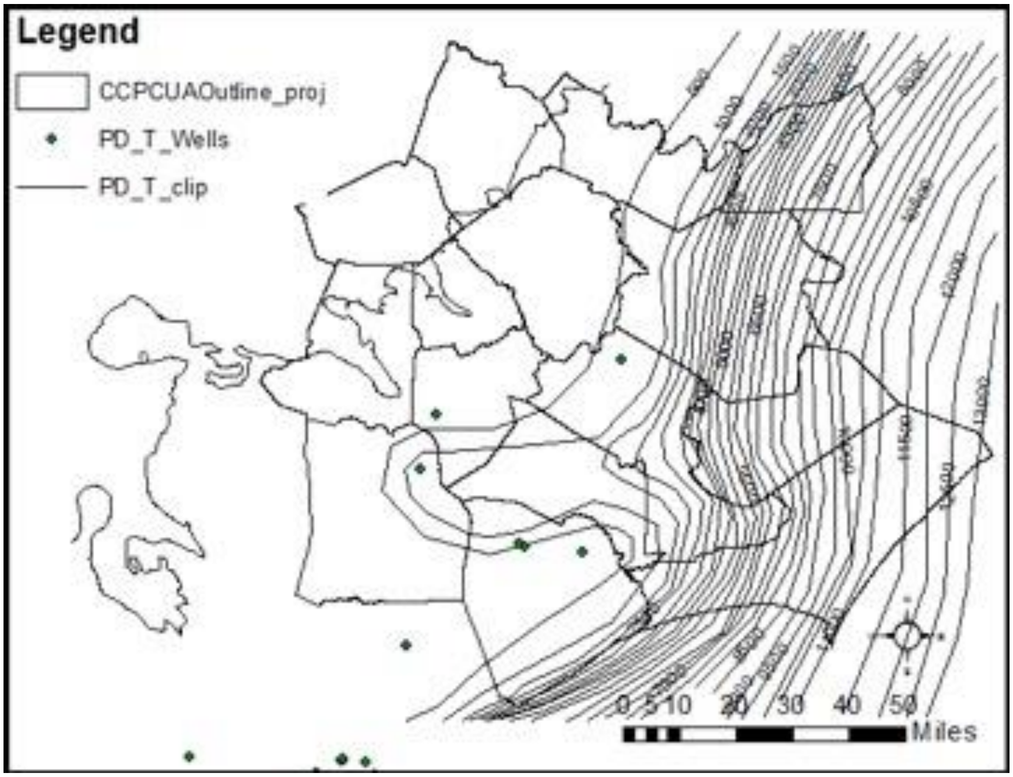

Figure 43. Interpolated transmissivity, Peedee aquifer. C.I.= 500’.

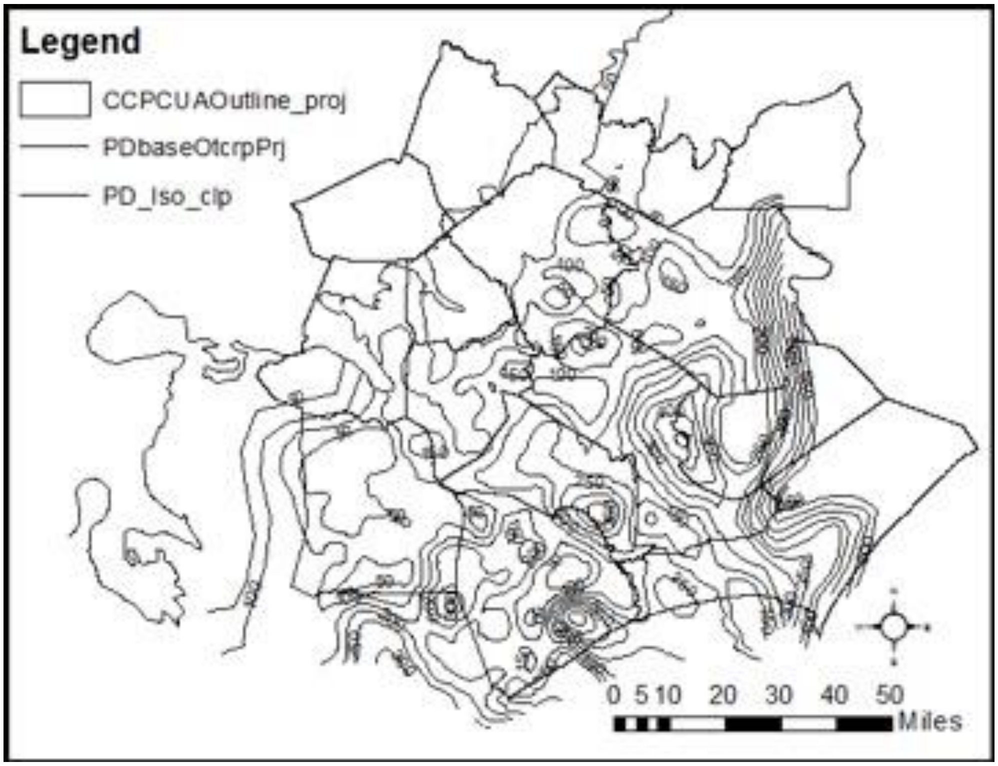

Figure 44. Isochore displaying thickness, Peedee aquifer. C.I.= 50'.

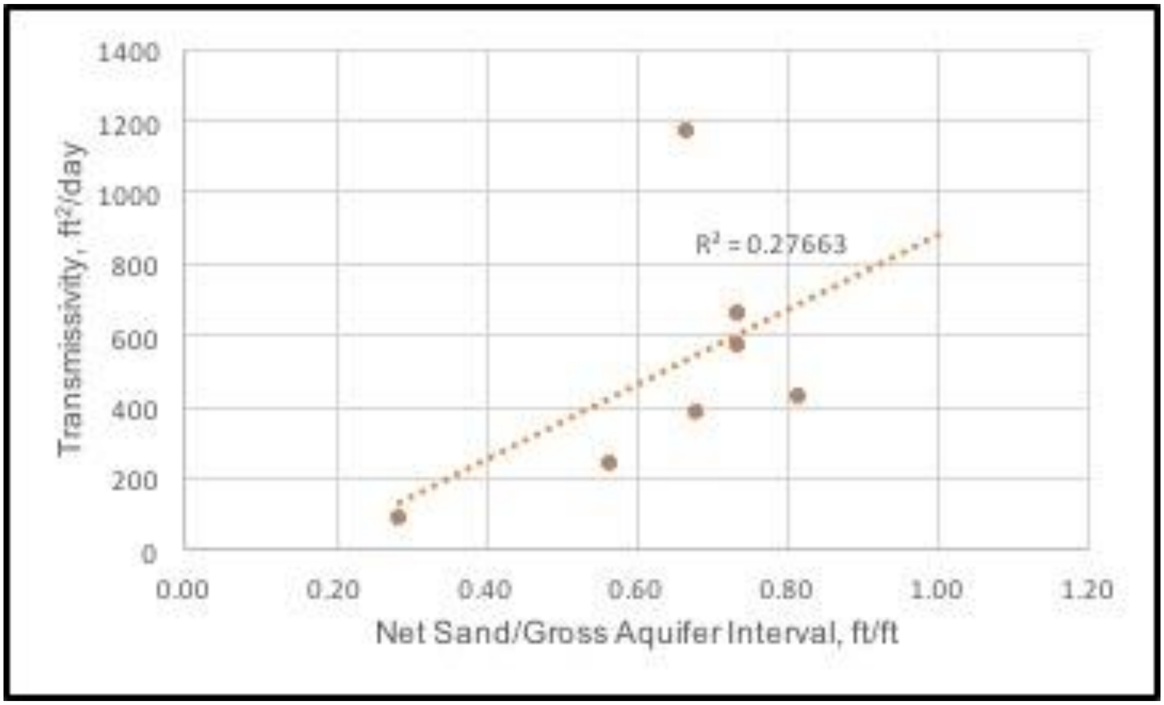

Figure 45. Scatter plot of the ration of net sand to gross aquifer interval vs. transmissivity for the Peedee aquifer.

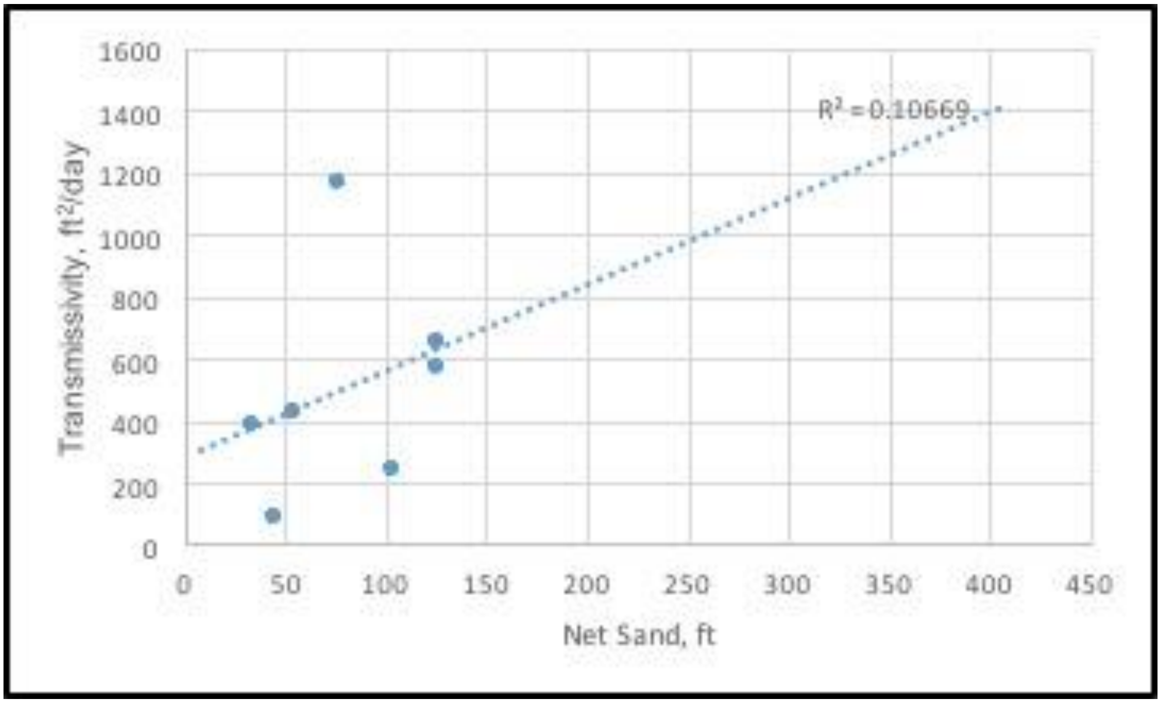

Figure 46. Scatter plot of the net sand vs. transmissivity for the Peedee aquifer.

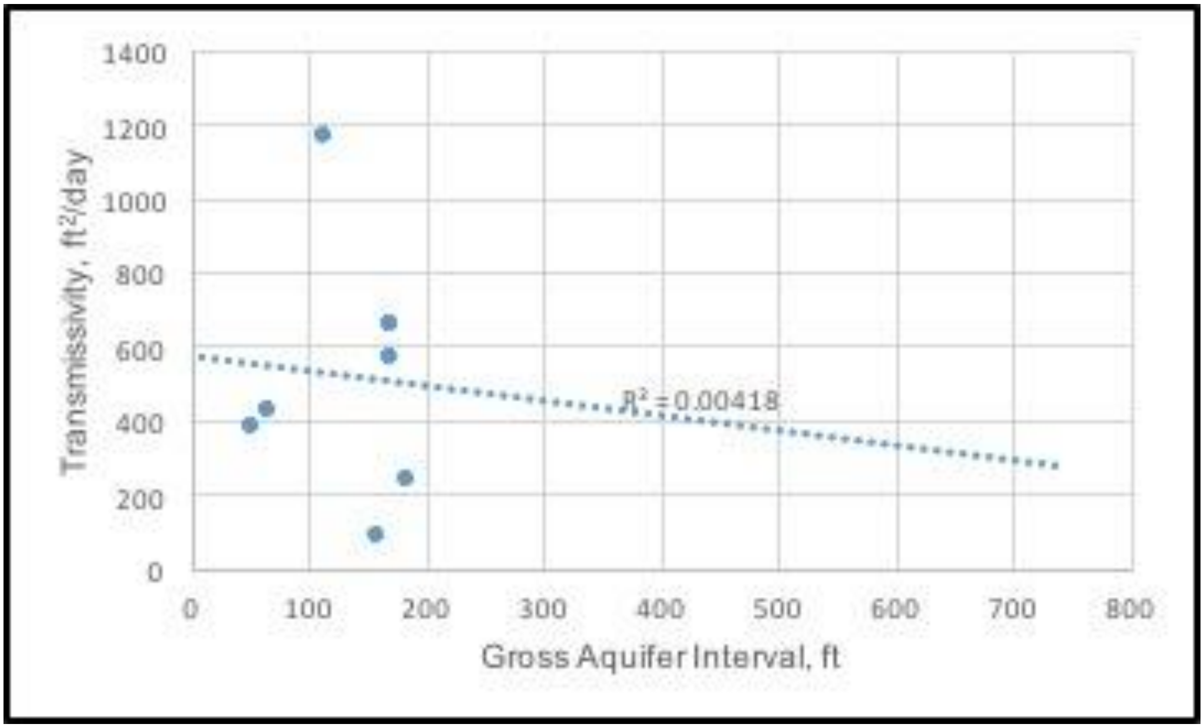

Figure 47. Scatter plot of the gross aquifer interval vs. transmissivity for the Peedee Creek aquifer.

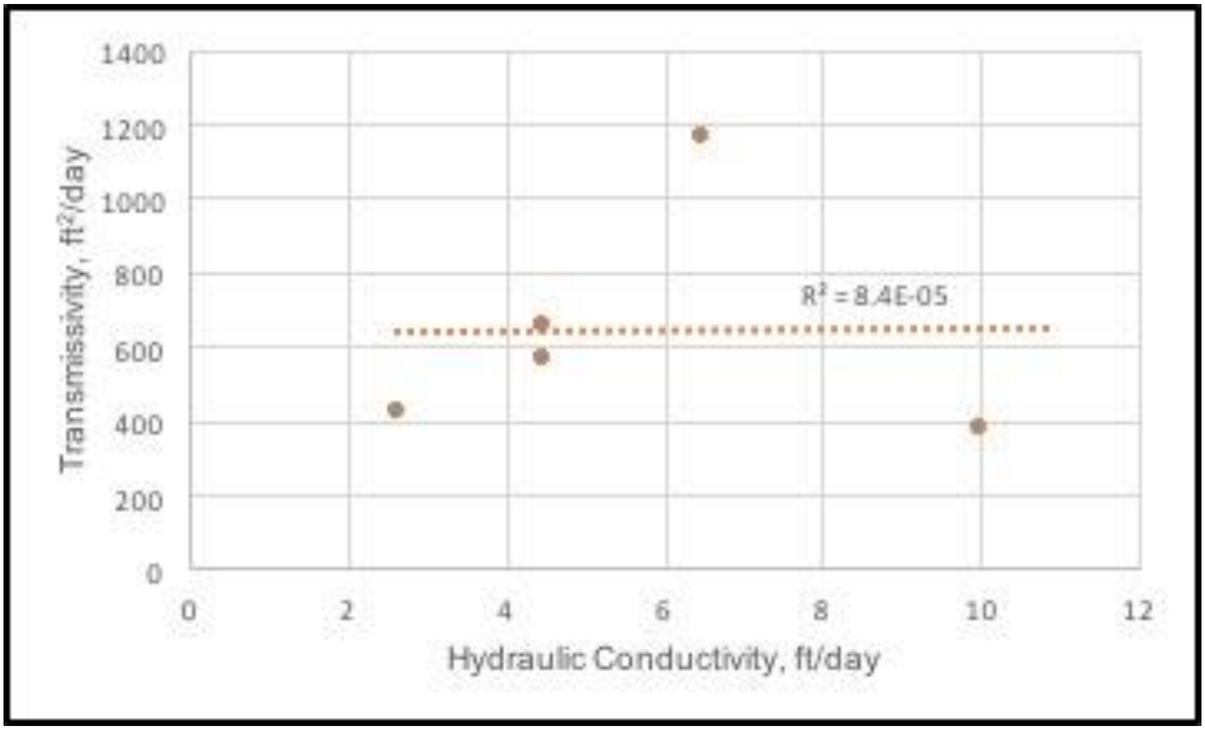

Figure 48. Scatter plot of the hydraulic conductivity vs. transmissivity for the Peedee aquifer.

The percentage of sand in the Peedee ranges from 28% to 100%, with a mean, median and mode of 70%, 71% and 74%, respectively (Table 6). One value of 28% is anomalous. Without that outlier, the range is smaller, at 55-100% net sand.

(a)

range	28-100
mean	70
median	71
mode	74

(b)

range	43-69
mean	57
median	60
mode	64

Table 10. Basic statistics for sand/gross interval (sand percentages) (a) Peedee aquifer, (b) Black Creek aquifer, %.

The transmissivity values for the Black Creek aquifer range from 289 to 2,941 ft^2/day (Table 5). The mean transmissivity for the Black Creek is 1,019 ft^2/day with a median of 911 ft^2/day and a mode of 481 ft^2/day. As noted for the Peedee aquifer, the Black Creek aquifer lacks sufficient data to definitively identify a trend. Again, following the convention of transmissivity increasing with increasing aquifer thickness, the transmissivity contour map (Figure 49) shows an increase to the east with the thickening of the Black Creek aquifer (Figure 50). Contrary to the results for the Peedee aquifer, the plot of gross aquifer interval to transmissivity tenuously supports this convention (Figure 51). Figure 52, a plot of the net sand versus transmissivity also tentatively supports the conventional mapping of transmissivity. Hydraulic conductivity versus transmissivity illustrates a positive correlation between the two variables and supports the conventional mapping (Figure 53). Only the plot of net sand to gross interval versus transmissivity refutes this convention, as it reflects decreasing transmissivity with an increasing volume of sand in the overall aquifer interval (Figure 54). Sand percentages in the Black Creek range from 43% to 69%, with a mean of 57%, a median of 60% and mode of 64% (Table 6).

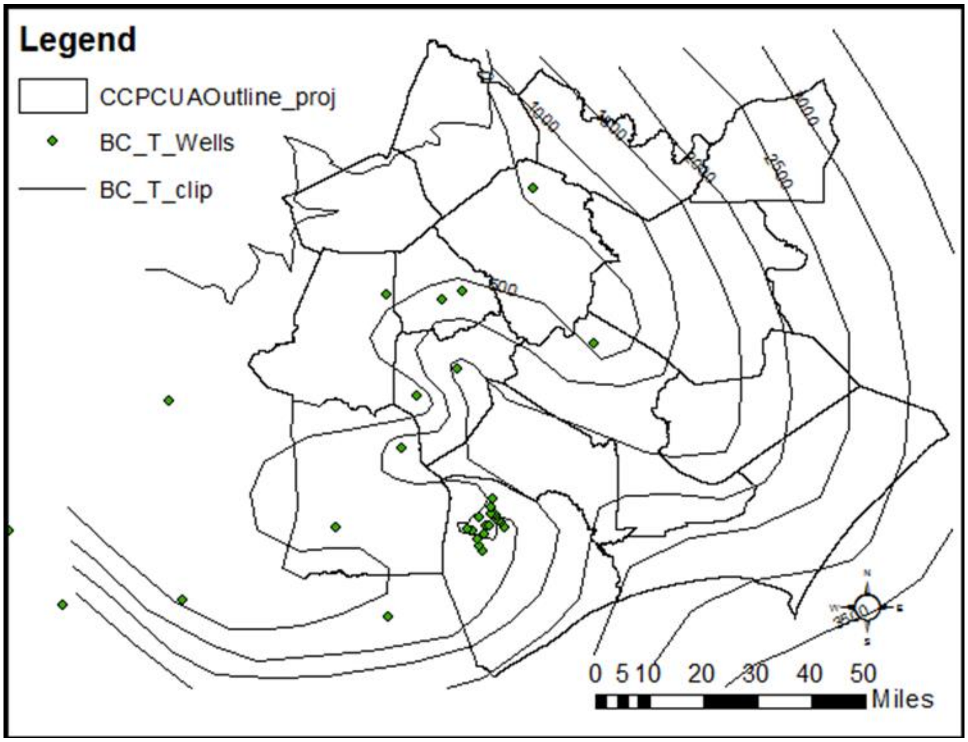

Figure 49. Interpolated transmissivity, Black Creek aquifer. C.I.= 500'.

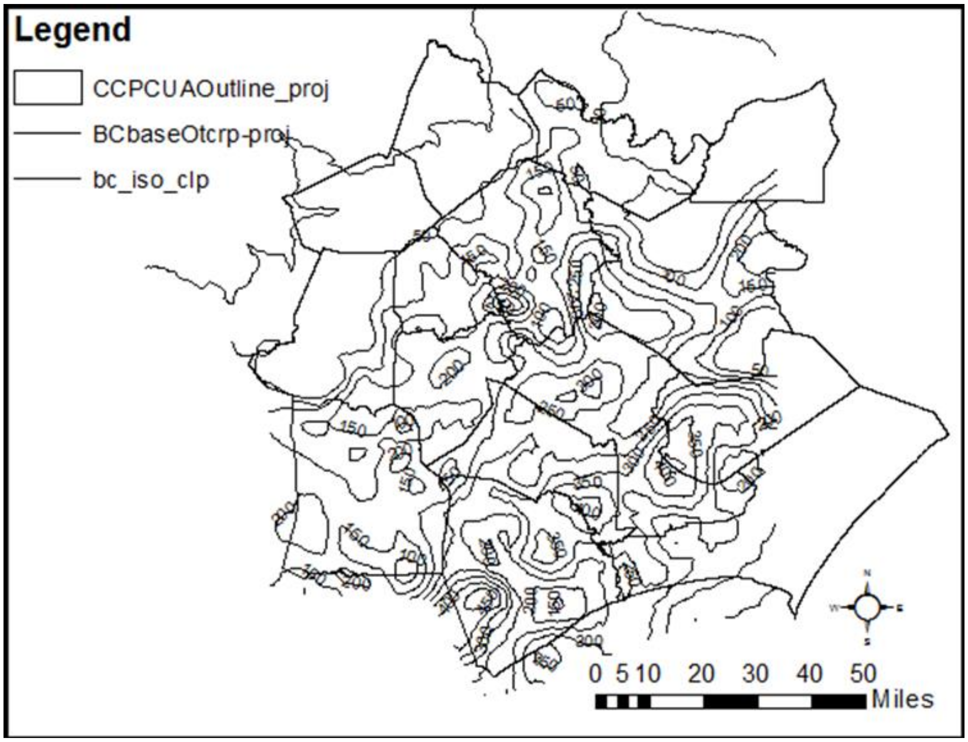

Figure 50. Isochore displaying thickness, Black Creek aquifer. C.I. =50’.

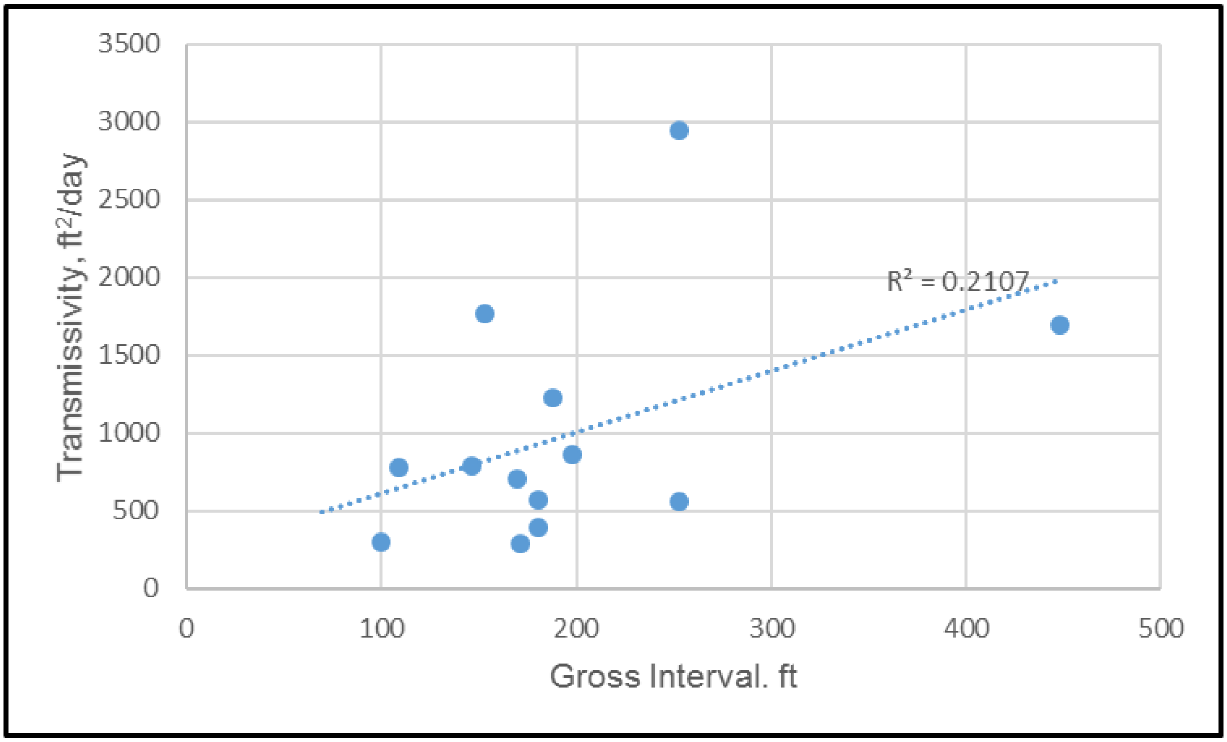

Figure 51. Scatter plot of the gross aquifer interval vs. transmissivity for the Black Creek aquifer.

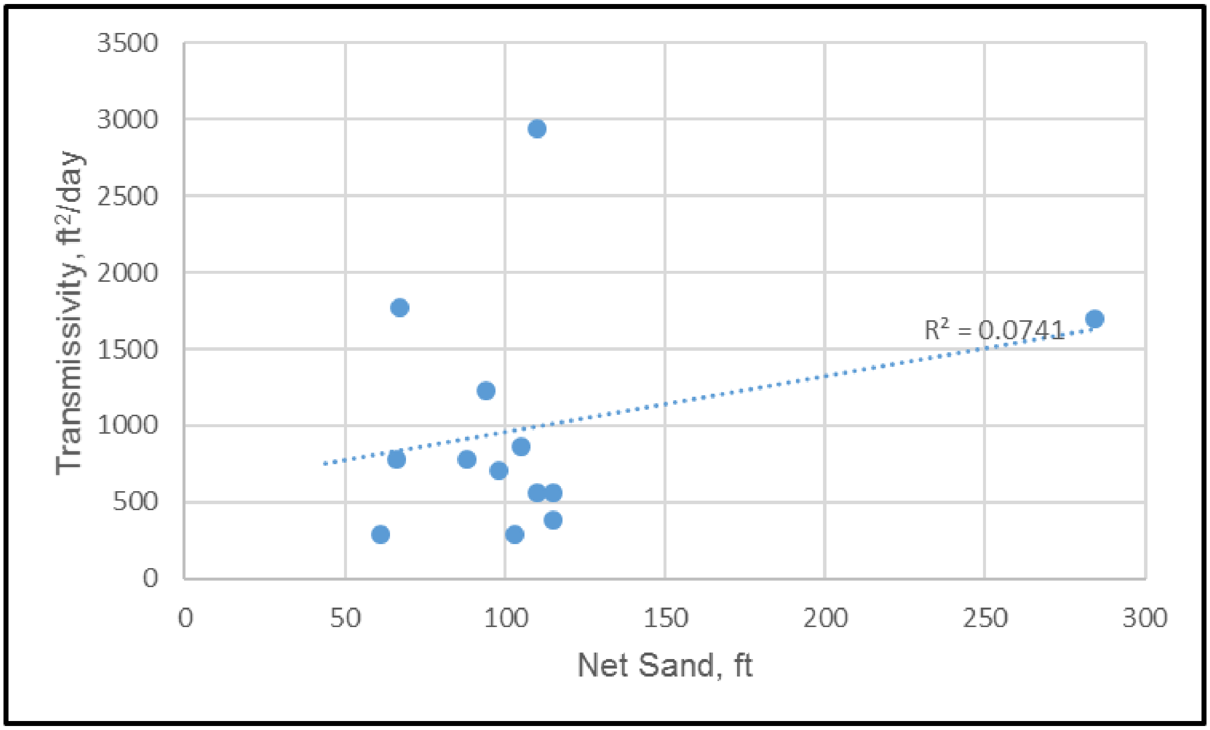

Figure 52. Scatter plot of the net sand vs. transmissivity for the Black Creek aquifer.

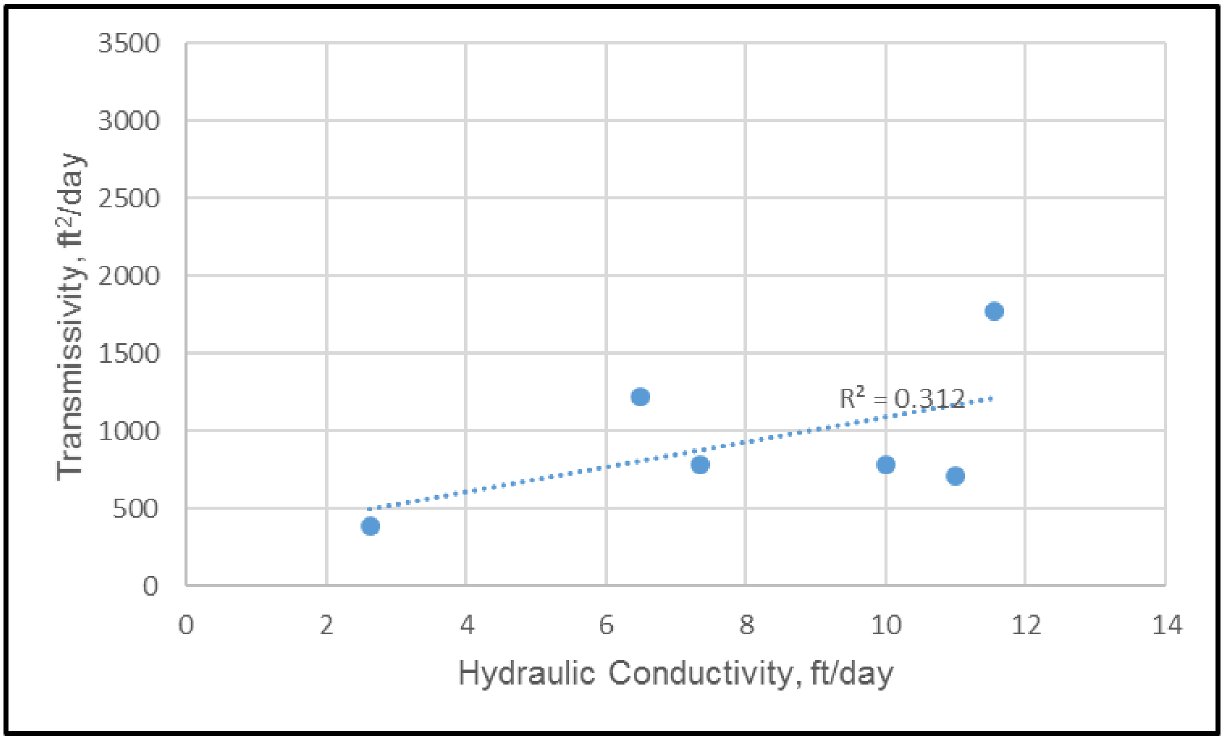

Figure 53. Plot of the hydraulic conductivity vs. transmissivity for the Black Creek aquifer.

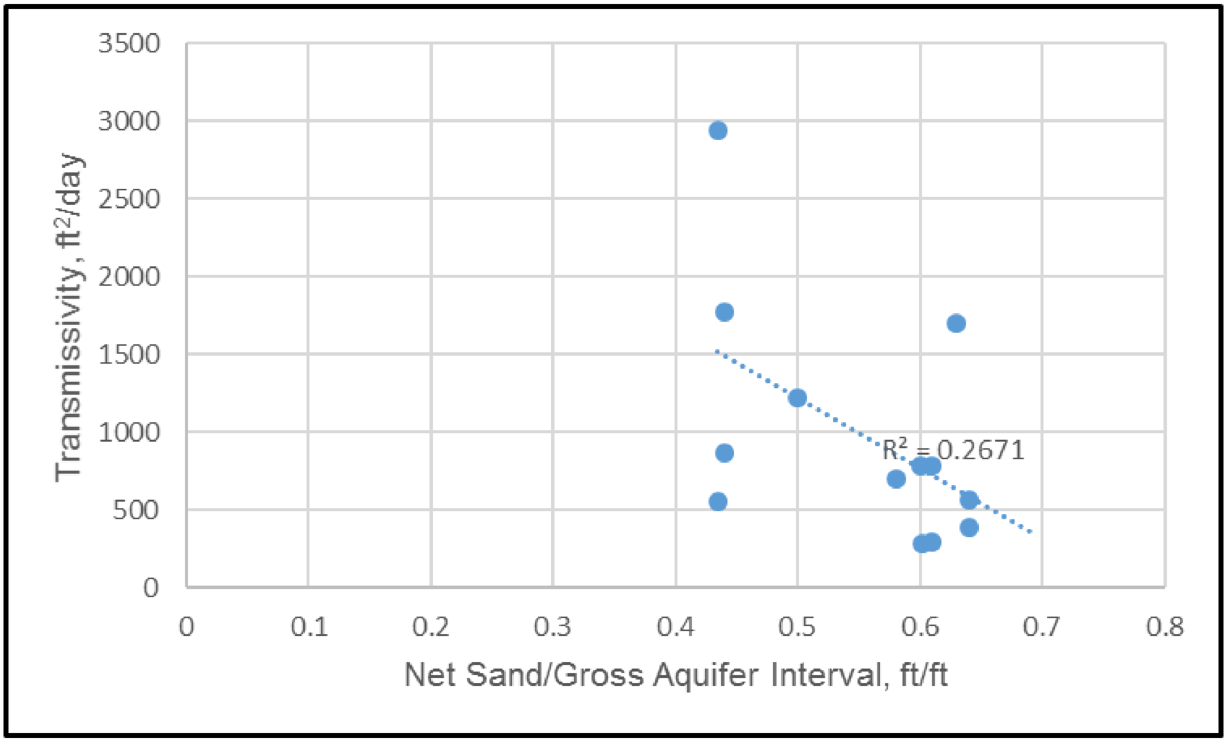

Figure 54. Plot of the ratio of net sand to gross aquifer interval vs. transmissivity for the Black Creek aquifer.

The transmissivity reclassification into three categories shows a large portion of the areas affected by the CCPCUA reductions have low transmissivities. They are assessed reclassifications as zone 1. The Peedee aquifer is missing in most of Edgecombe and Wilson counties and has low transmissivities of less than 553 ft^2/day in most of Martin, Pitt, Greene, Wayne, Lenoir, Duplin and Onslow counties (Figure 55). In the Black Creek aquifer, the easternmost CCPCUA counties, including most of Edgecombe, Wilson, Pitt, Greene, Wayne and Duplin, also have low transmissivities (Figure 56).

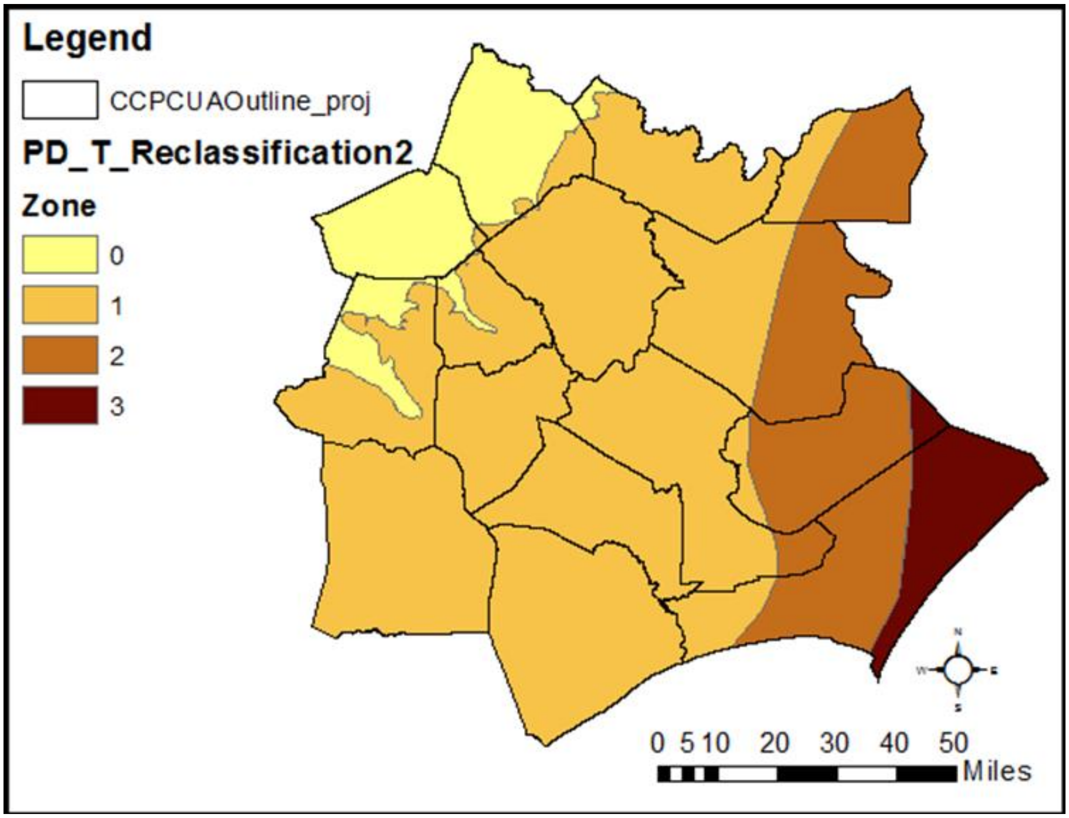

Figure 55. Thematic reclassified map displaying transmissivity, Peedee aquifer.

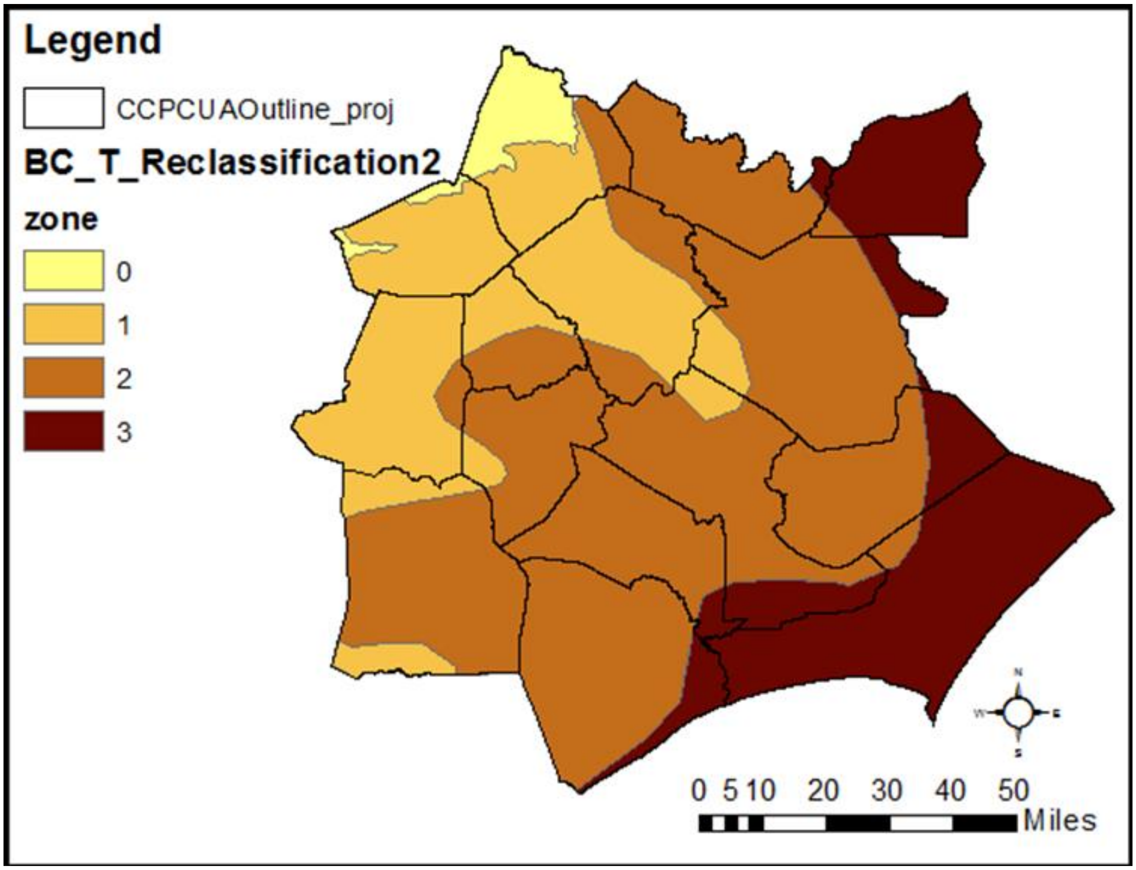

Figure 56. Thematic reclassified map displaying transmissivity, Black Creek aquifer.

Safe drawdown for the Peedee and Black Creek aquifers (Figures 57 and 58) follow the same trend as the aquifers' gross thickness (Figures 44 and 50), trending northeast, southwest, and thickening to the east, southeast. The safe drawdown values range from zero at the outcrop to the east, to greater than 1,900 feet for the Peedee and 6,500 feet for the Black Creek. The smaller the safe drawdown, the less water that is available before the aquifer experiences detrimental effects. Therefore, the small available drawdown areas are considered the most vulnerable to changes in pumping and are assessed reclassifications of 1 (Figures 59 and 60).

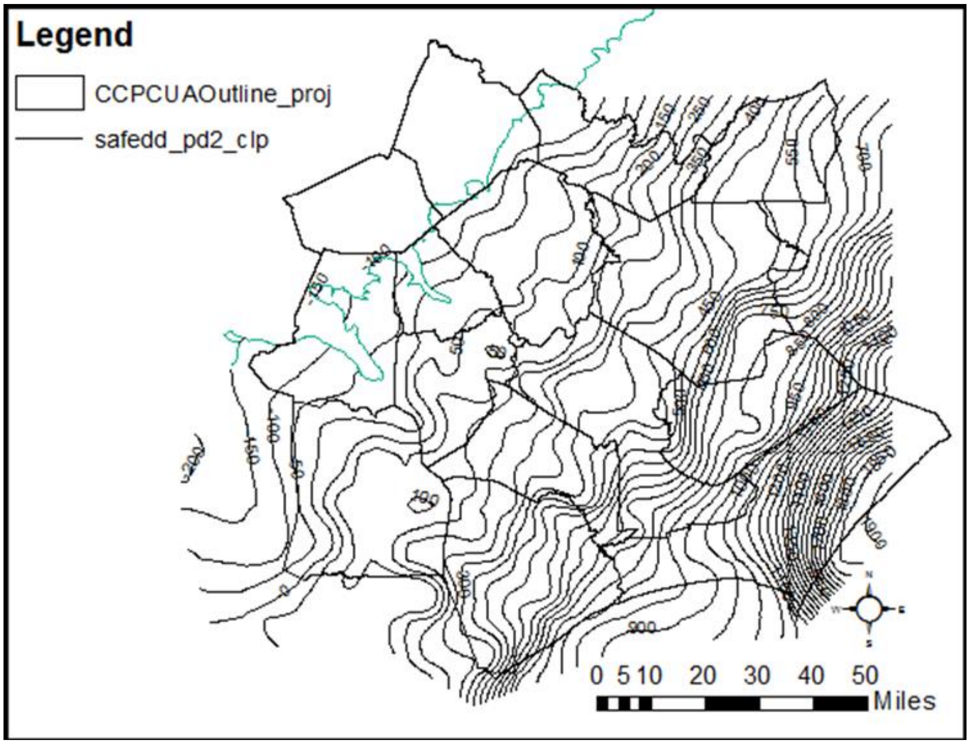

Figure 57. Contour map, Peedee aquifer displaying safe drawdown.

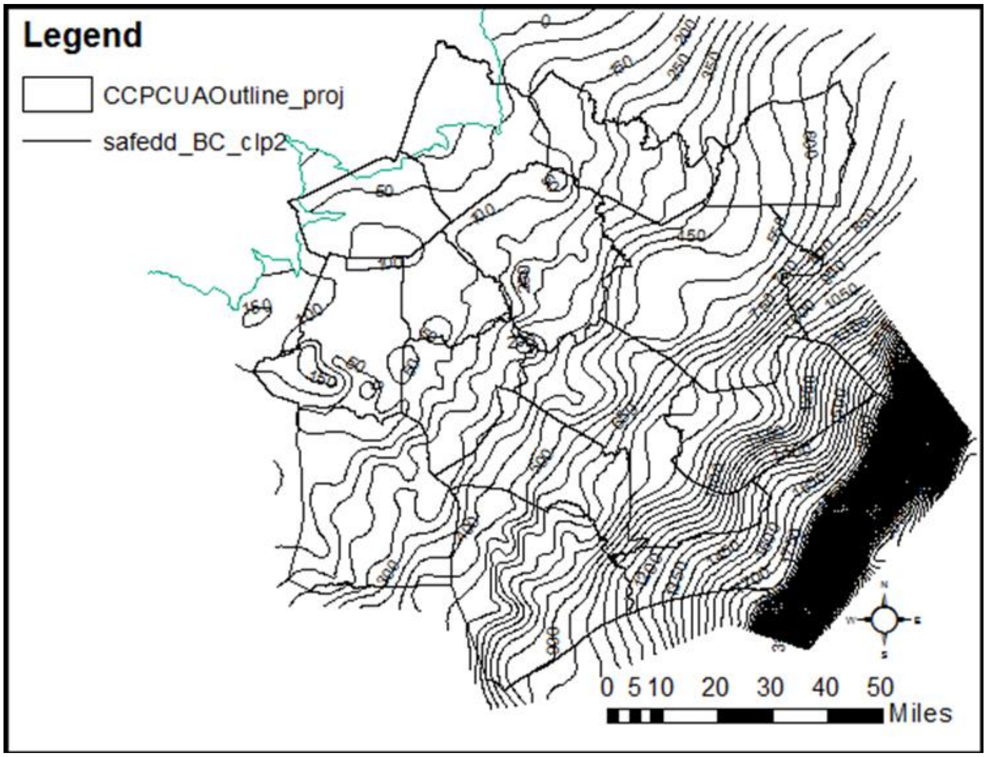

Figure 58. Contour map, Black Creek aquifer displaying safe drawdown.

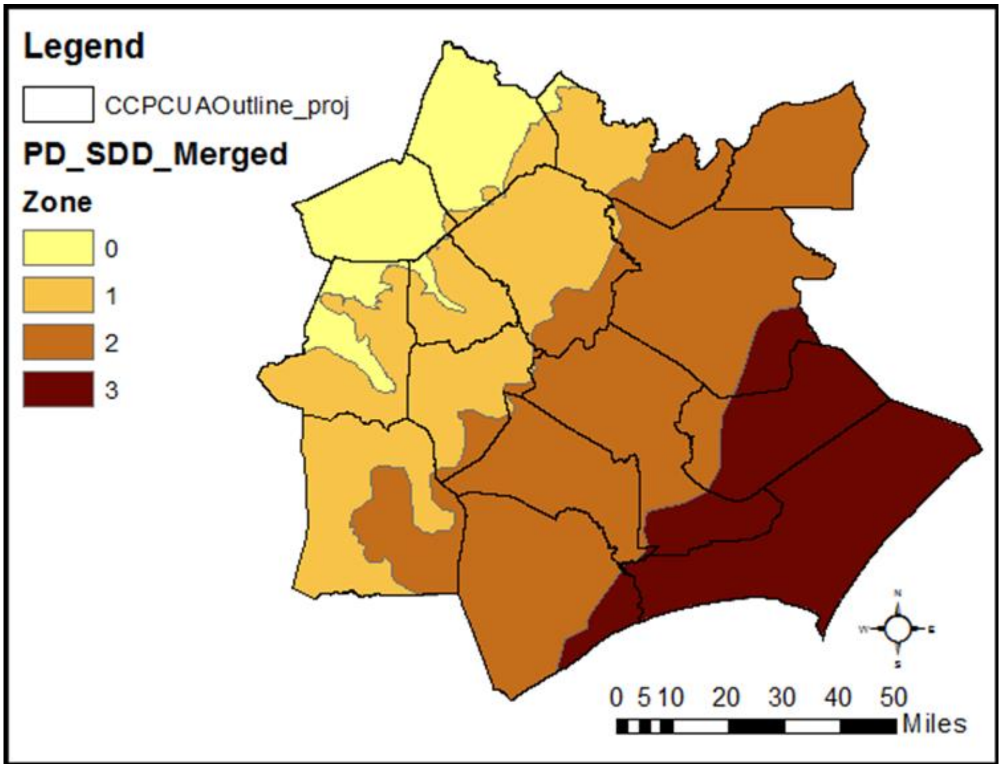

Figure 59. Thematic reclassified map displaying safe drawdown, Peedee aquifer.

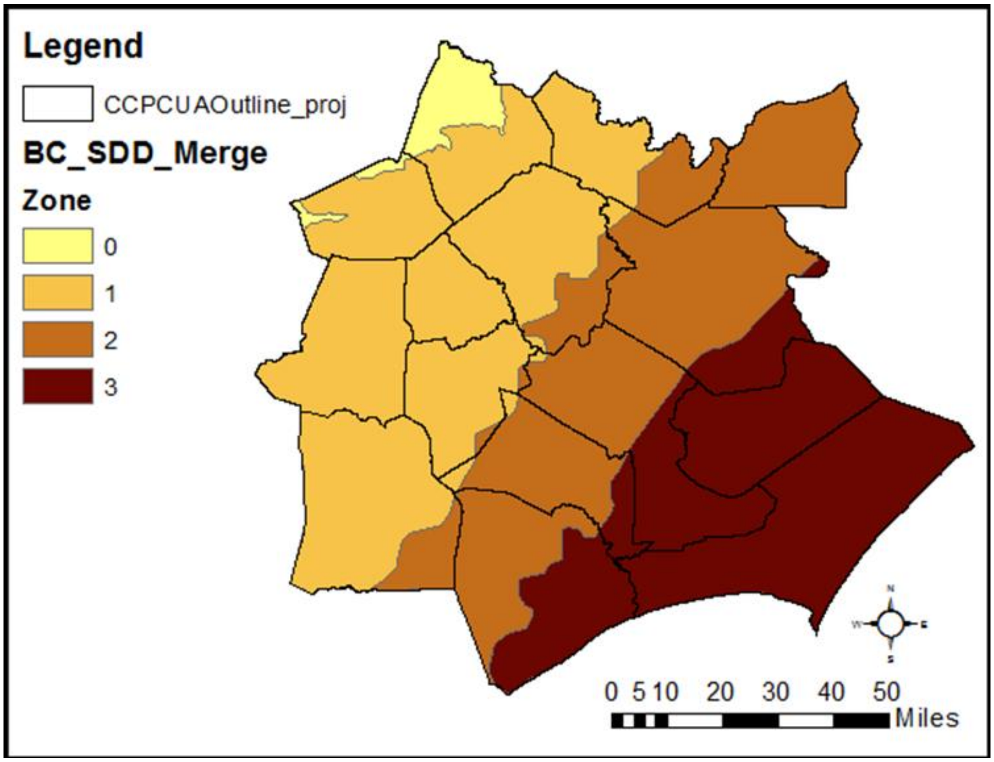

Figure 60. Thematic reclassified map displaying safe drawdown, Black Creek aquifer.

A.2.2. C-2 Demands

In 2002, demand varied widely throughout the CCPCUA, with ranges from 0.01 to 10,000 million gallons of water per day (Figure 61). The average demand for water was approximately one half a million gallons per day. The median and mode demand values for the CCPCUA in 2002 were 0.227 and 0.131 million gallons. Of the 104 providers within the CCPCUA, twenty-four (24) providers had demands of greater than 1 million gallons per day; only two (2), the city of Greenville and Rocky Mount, had demands of greater than 10 million gallons per day (Table 7). Projected Demand is not projected to increase by 2020 (Table 8). Figure 62 illustrates the reclassified demand areas. The higher demand areas must continue to provide the required water supplies, therefore cannot withstand major pumping reductions. The high demand areas are reclassified as zone 1, as the citizens of these areas would be highly impacted by reduced pumping.

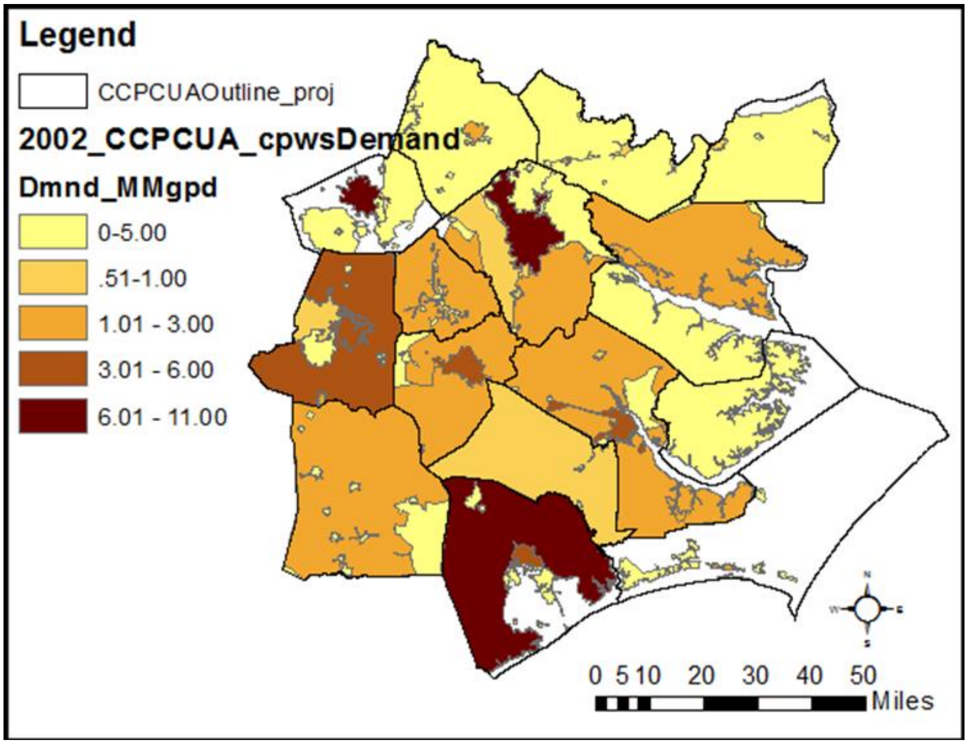

Figure 61. Thematic map displaying demand, CCPCUA.

Median	0.99
Median	0.24
Mode	0.01
Range	0.01-11.407

Table 11. Basic statistics for 2002 CCPCUA demands.

Mean	1.35
Median	0.33
Mode	0.05
Range	0.018-18.032

Table 12. Basic statistics for the 2020 CCPCUA demands.

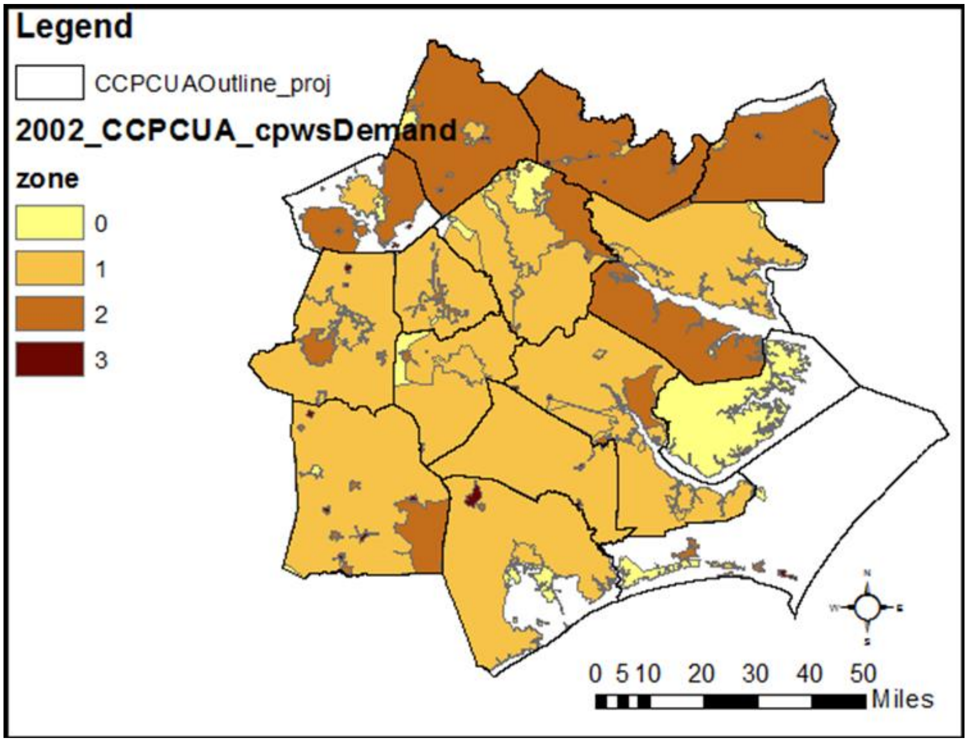

Figure 62. Thematic reclassified map displaying demand.

A.2.3. C-3 Population

The CCPCUA is composed of 632 individual census block groups of varying taxpayer population sizes, ranging from 82 to 12,779 people. The geographic sizes for each census block range from 1.2 x 10^5 m^2 to 1.3 x 10^{12} m^2 (0.04 – 502 square miles) (Figure 63). The population densities vary from 0 to 175,000 people/square miles, with the high population density centers located adjacent to a surface water body (Figure 64). The reclassified population map, Figure 65, illustrates the sparse population density of the majority of the CCPCUA; the areas where large populations would not be impacted by pumping changes.

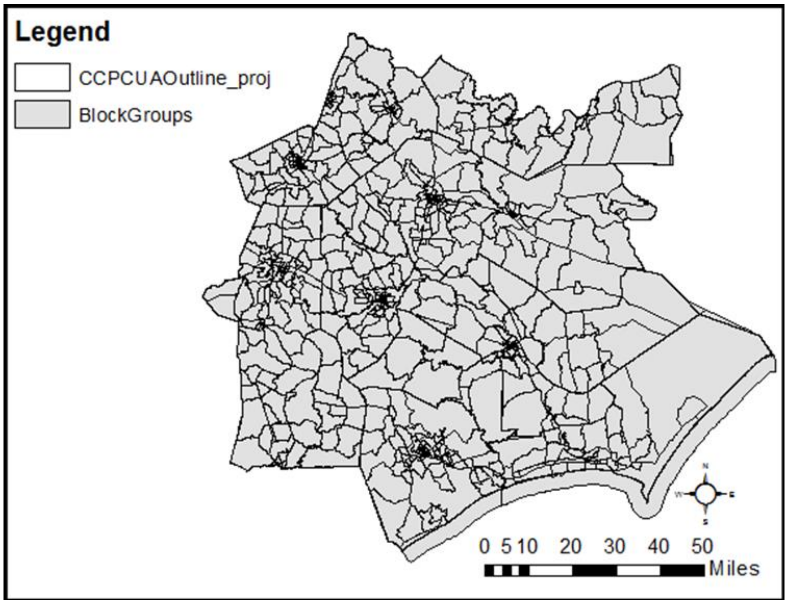

Figure 63. Block groups in CCPCUA, year 2000.

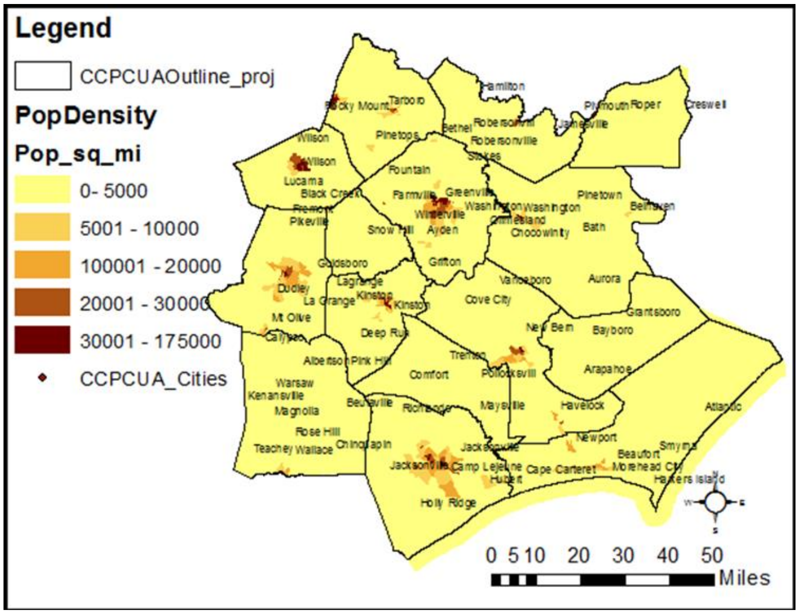

Figure 64. Population densities, CCPCUA.

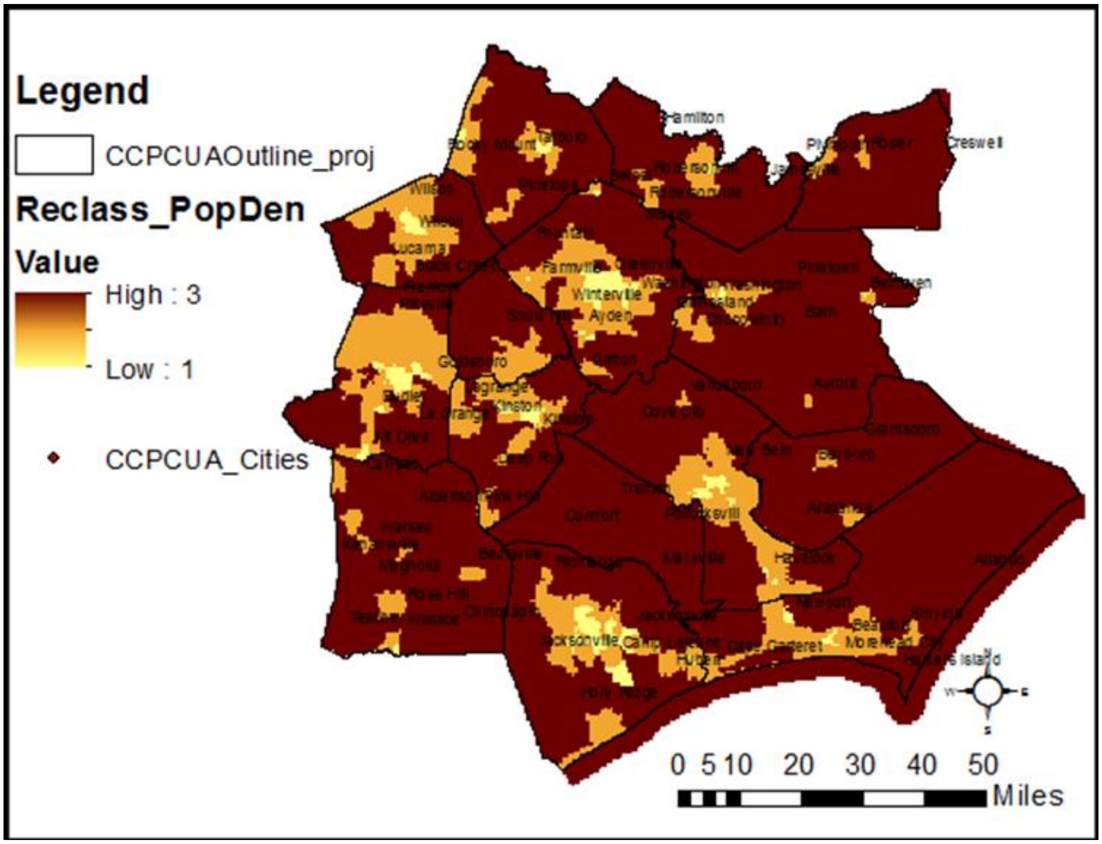

Figure 65. Thematic reclassified map displaying population densities, CCPCUA.

Chloride values for the Peedee and Black Creek aquifers (Figures 66 and 67) and aquifer truncation by erosion control the configuration of the aquifer zones. The Cretaceous aquifers are conformable, all dipping to the east (Figures 38 and 40). The aquifers thin to the west and outcrop at the land surface (43 and 49), creating the westernmost boundary for the analysis area. The eastern boundary is controlled by higher salinity water as the aquifers dip toward the land, sea interface. As illustrated in Figures 68 and 69, the Peedee and the Black Creek aquifer zones roughly parallel the strike of each aquifer.

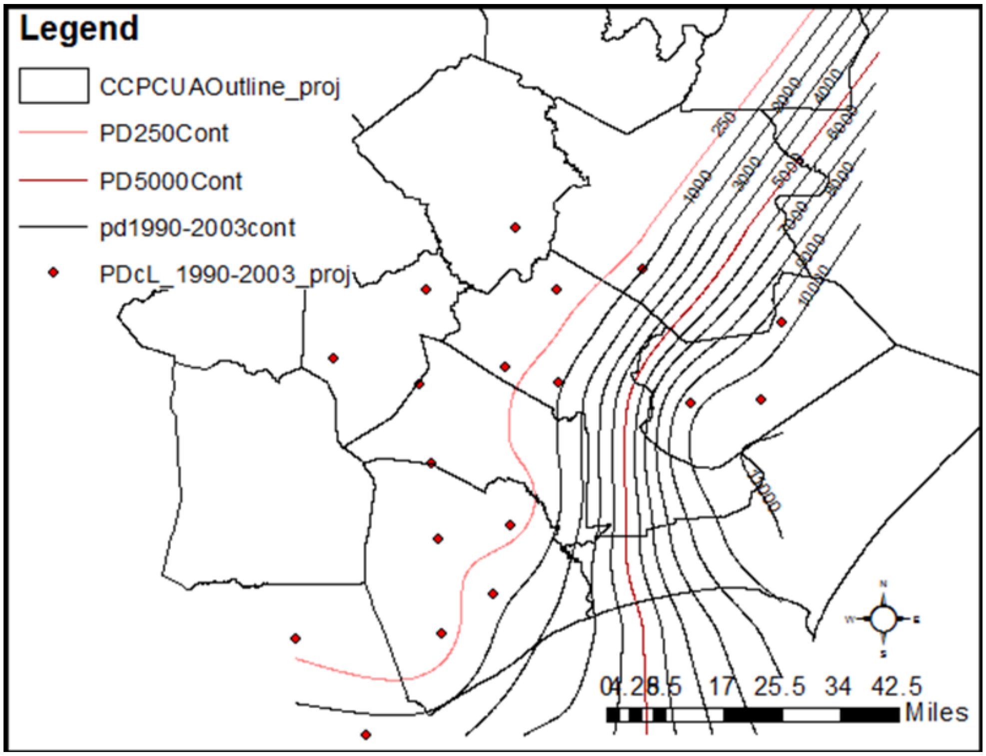

Figure 66. Contour map displaying chlorides, Peedee aquifer. C.I.=1,000ppm.

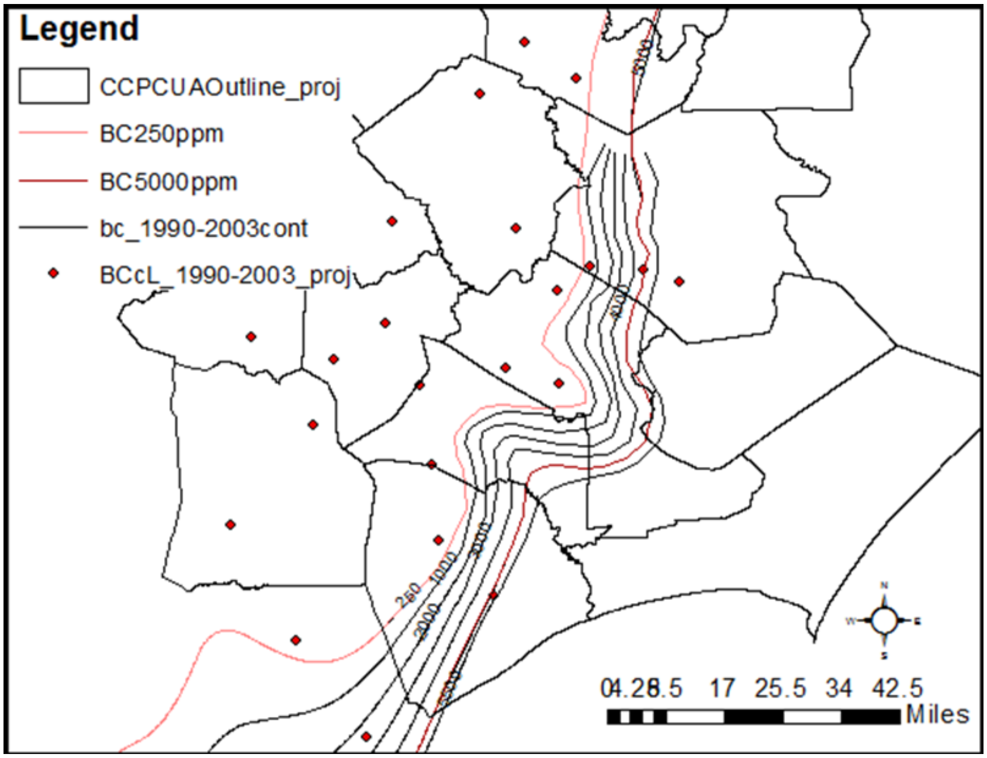

Figure 67. Contour map displaying chlorides, Black Creek aquifer. C.I.=1,000ppm.

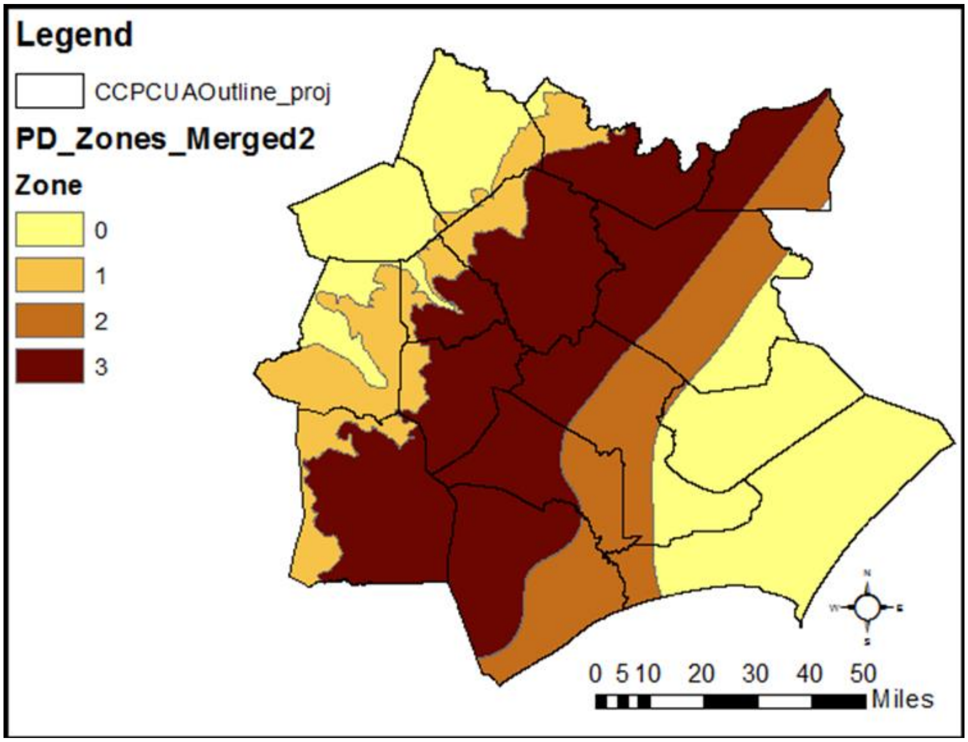

Figure 68. Thematic reclassified layer displaying available Peedee groundwater zones within CCPCUA.

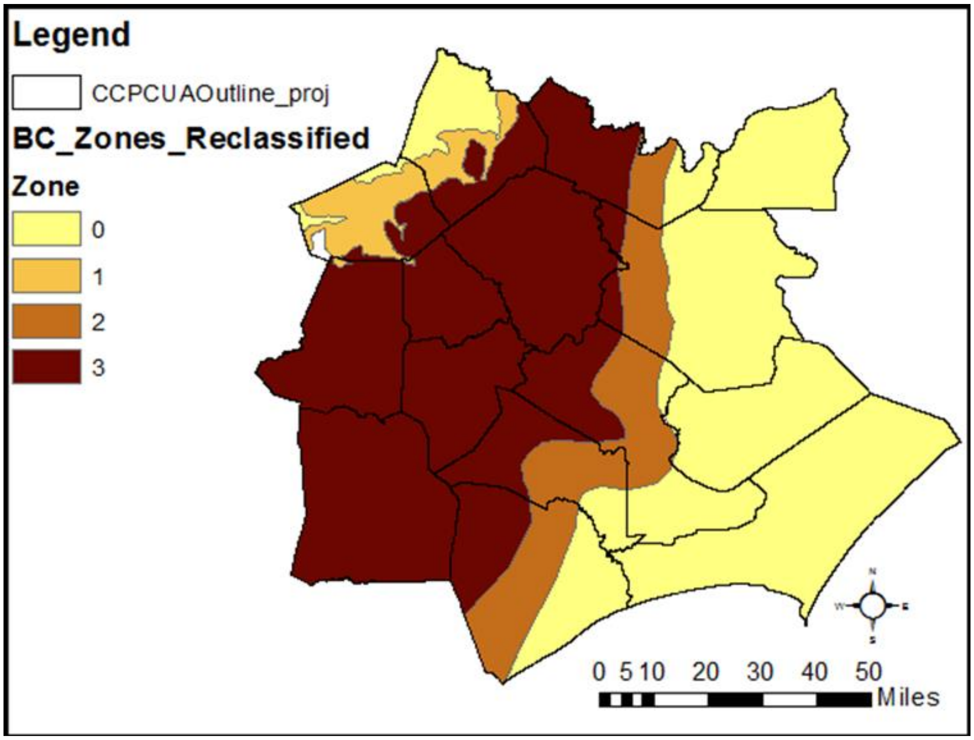

Figure 69. Thematic reclassified layer displaying available Black Creek groundwater zones within CCPCUA.

A.2.4. C-4 Available groundwater

Chloride values for the Peedee and Black Creek aquifers (Figures 66 and 67) aquifer pinchouts control the configuration of the aquifer zones. The Cretaceous aquifers are conformable, all dipping to the east (Figures 38 and 40). The aquifers pinchout to the west as each aquifer truncates at the land surface, creating the westernmost boundary for the analysis area. The eastern boundary is controlled by higher salinity water as the aquifers dip toward the land, sea interface. Figures 67 and 68 illustrate the aquifer zones for the Peedee and the Black Creek aquifers which roughly parallel the strike of each formation.

A.2.5. C-5 Alternate water source, surface water

Figure 70 displays the reclassified Thiessen polygons illustrating the range of interpolated 7Q10 values in the CCPCUA. The values range from 0.03 to a maximum of 350 ft^3/second. The areas of the highest 7Q10 values are along the upper reaches of the Tar and Neuse Rivers in the western portion of the Pamlico and Neuse River basins.

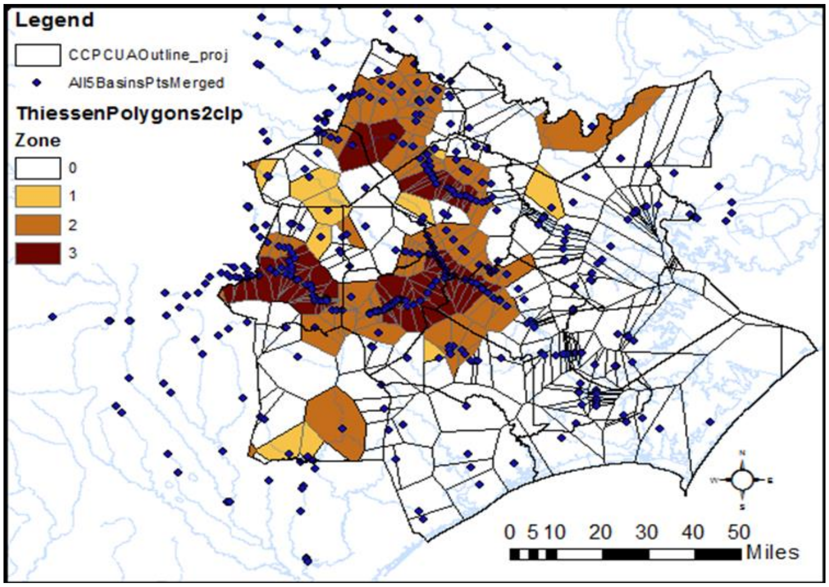

Figure 70. Thematic reclassified Theissen polygons illustrating the range of interpolated 7Q10 values in the CCPCUA.

A.2.6. C-6 Financial capability

Figures 71 and 72 show the average income and taxes paid in each block group in the CCPCUA. Thirty-seven water provider areas are subject to mandated pumping reductions within the CCPCUA (Figure 73), with taxpaying populations in each provider unit ranging from 20 to approximately 78,000 people (Figure 74). Taxes for each water provider areas are shown in Figure 75. The mandated pumping reductions, over an 11-year time period from the end of the first phase in 2008 until the end of the reduction periods in 2016 (Table 9) range from a total of approximately 280 million gallons for water providers in Edgecombe County to 18 billion, for Lenoir County providers. The individual provider's theoretical maximum pumping reductions range from 65 million to 11 billion gallons of water. The three largest reductions in pumping are mandated for the City of Kinston (11.5 billion gallons), Onslow County (9.5 billion gallons) and the City of New Bern (7.0 billion gallons).

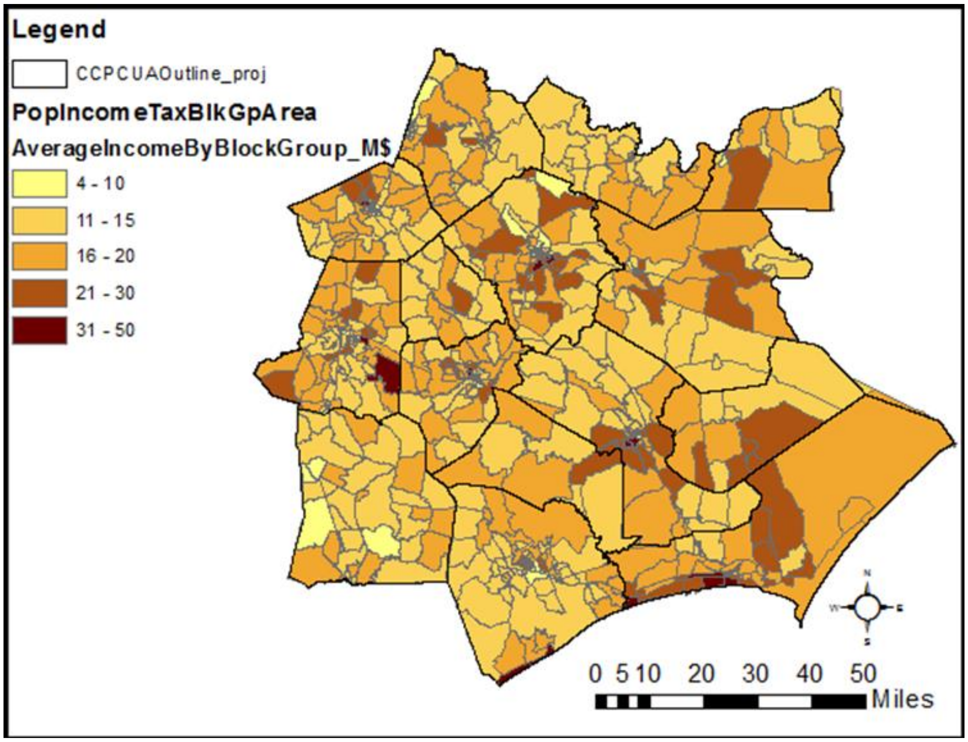

Figure 71. Average income in each block group in the CCPCUA; Thousand (m) $.

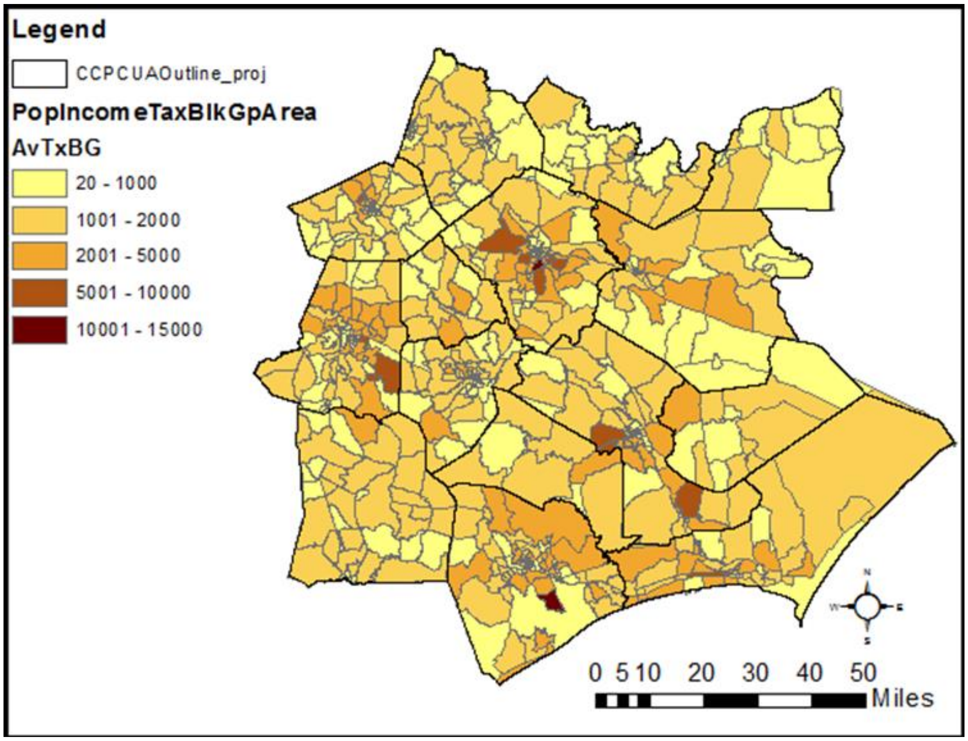

Figure 72. Average taxes paid in each block group in the CCPCUA.

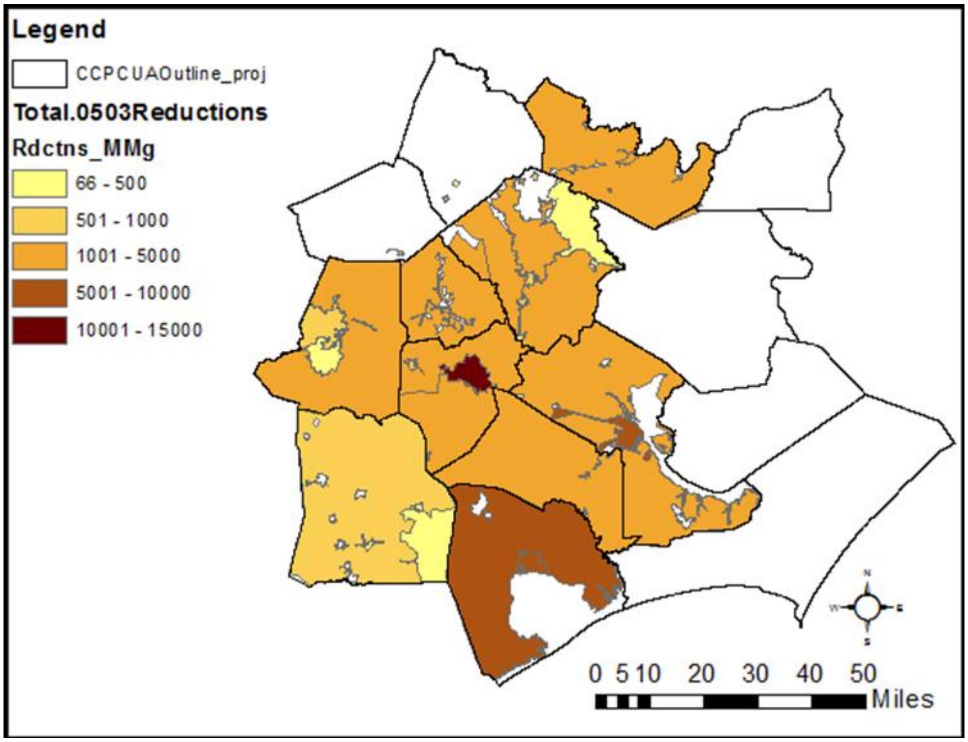

Figure 73. Mandated pumping reductions of 37 water providers areas within the CCPCUA, MMG.

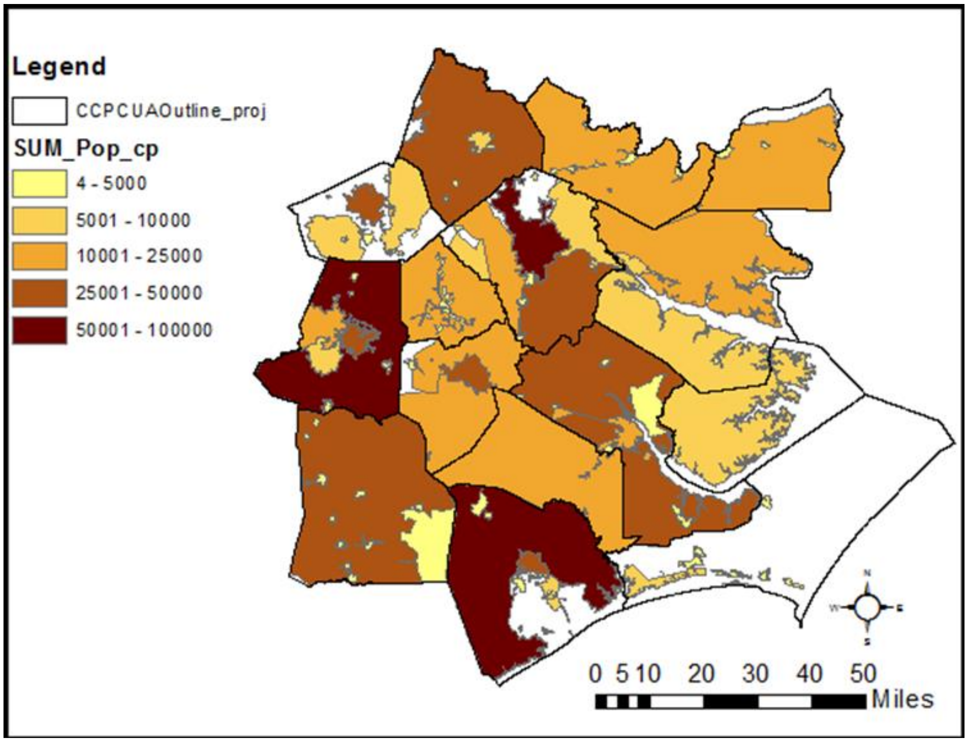

Figure 74. Taxpaying populations within each providers unit in the CCPCUA.

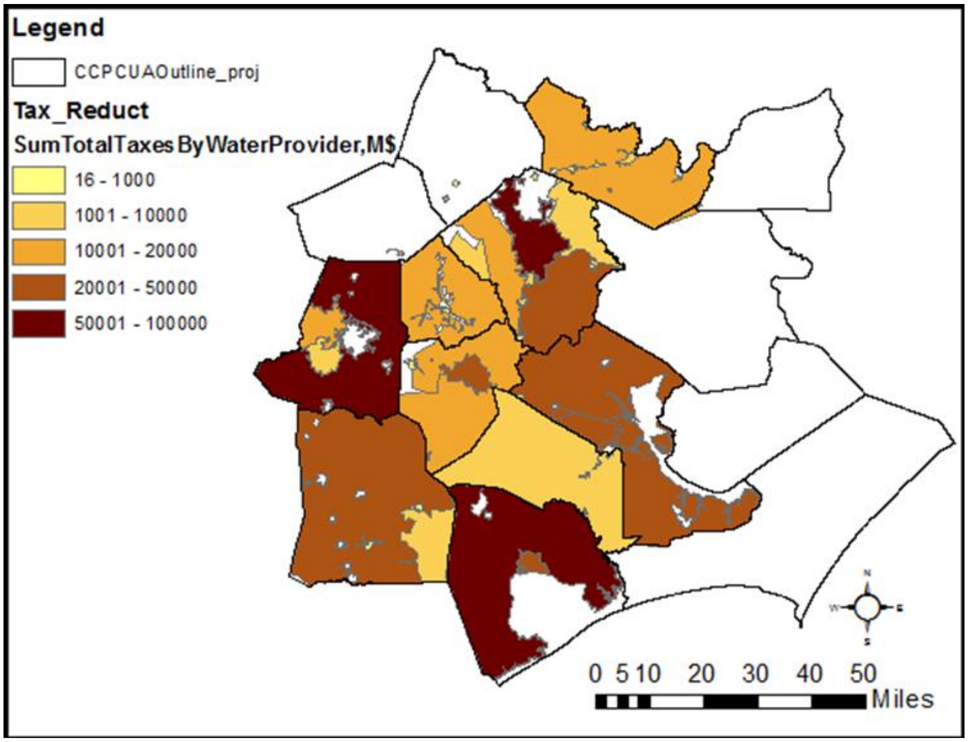

Figure 75. Taxes paid in each provider unit in the CCPCUA, M$.

Counties	Water Reduced In 3 Phases
Up to 30% reductions	
Duplin	1,843,375,756
Wayne	2,785,696,200
Wilson	367,186,140
Edgecombe	280,996,227
Martin	910,006,857
Up to 75% reductions	
Pitt	13,008,259,593
Martin	2,576,672,325
Craven	11,426,094,293
Greene	4,858,836,143
Jones	1,115,721,000
Lenoir	18,446,344,524
Onslow	16,170,646,950

Table 13. Hypothetical maximum reductions, by county, as mandated by the CCPCUA regulation.

The costs for the various pumping reductions and alternative water sources are shown on Tables 10-13. The average total costs, including the capital and O and M costs for 11 years, are $30.5 million for the RO plant, $34 million for the new well field and treatment plant, $65 million for the surface water treatment plant and $33 billion for the bottled water option.

Water Source	**Information Source**	**Capital Cost, $**	**O&M Cost, $/year**	**O&M Cost, $**	**Sum Capital and O&M costs, $**	**Comments**
Groundwater RO	Carolla Engineering, 2016$	11,180,718	1,825,000	14,595,416		Based on plant size
	Rivers & Associates, 2005$	23,115,870	1,329,482	13,595,176		reduced from 6MMgpd
	S. Hill, 2016$	14,907,624				Bogue Banks water Corp
Average		**16,401,404**		**14,095,296**	**30,496,700**	

Table 14. Cost estimates for groundwater RO. Capital costs adjusted for inflation to 2002. O&M costs adjusted for inflation (2008-2018) and net present value.

Water Source	**Information Source**	**Capital Cost, $**	**O&M Cost, $/year**	**O&M Cost, $**	**Sum Capital and O&M costs, $**	**Comments**
Bottled Water, 2016$	Officesnax.com		11,100,000	**107,973,529**		http://www.officesnax.us/; $8.89/4 gallons

Table 15. Cost estimates for bottled water. Costs adjusted for inflation to 2002.

Water Provider	Percent Reductions	RO Average Tax Increase/year ($)	New Well Field Average Tax Increase/year ($)	Water Treatment Plant Average Tax Increase/year ($)
Chinquapin Water Association	30	35	37	74
Duplin County	30	31	33	65
Fork Township SD	30	70	75	149
Southern Wayne SD	30	74	78	157
Town of Beulaville	30	1628	1734	3469
Town of Greenevers	30	592	631	1262
Town of Hamilton	30	4990	5317	10634
Town of Macclesfield	30	1473	1569	3139
Town of Pinetops	30	875	932	1865
Town of Robersonville	30	6539	6968	13936
Town of Stantonsburg	30	7918	8438	16875
Wayne WD Combined	30	49	53	105

Table 16. Hypothetical average per capita reductions, per year, in taxes by permitted water provider in declining water level zone, resulting from maximum reductions as mandated by the CCPCUA regulation.

Water Provider	Percent Reductions	RO Average Tax Increase/year ($)	New Well Field Average Tax Increase/year ($)	Water Treatment Plant Average Tax Increase/year ($)
Bell Arthur Water Corporation	75	260	277	554
City of Greenville	75	43	45	91
City of Jacksonville	75	348	371	742
City of Kinston	75	660	703	1407
City of New Bern	75	460	491	981
Craven County	75	139	148	296
Deep Run Water Corporation	75	262	279	559
Eastern Pines WC	75	181	193	386
Greene County RWS	75	326	347	695
Jones County	75	163	174	348
Martin County	75	59	62	125
North Lenoir Water Corporation	75	380	405	809
Onslow County	75	184	196	393
Stokes Regional Water Corporation	75	88	94	188
Town of Ayden	75	1154	1230	2460
Town of Bethel	75	1226	1306	2612
Town of Dover	75	7068	7531	15062
Town of Farmville	75	618	659	1318
Town of Grifton	75	2170	2312	4625
Town of Hookerton	75	6416	6836	13673
Town of La Grange	75	2809	2993	5987
Town of Pink Hill	75	3066	3267	6534
Town of Snow Hill	75	2844	3030	6061
Town of Williamston	75	630	671	1343
Town of Winterville	75	329	351	701

Table 17. Hypothetical average per capita reductions, per year, in taxes by permitted water provider in dewatered or salt water encroachment water level zone, resulting from maximum reductions as mandated by the CCPCUA regulation.

The estimated monetary increases incurred by taxpayers in various provider units are shown in Table 14 for the declining water level zone and Table 15 for dewatered or salt water encroachment water level zone. The total mandated reductions and the percent change to the taxpayers for the different alternatives, by service provider, are shown on Table 14 for the declining water level zone and Table 15 for dewatered or salt water encroachment zone. The increased costs varied by each provider unit, ranging from $31 per taxpayer to $7,918 per taxpayer for the groundwater RO option. Similarly, the new well field ranges from $33 to $8438 per capita. Water treatment plants cost the average taxpayer $65 to $16,875. The increased taxes per taxpayer vary from 4% for the groundwater RO option to 1853% for water treatment plants. Twelve water providers suffer tax increase of 20% or less for the RO option, 11 providers for the new well field, and only 8 providers would experience less than a 20% increase in taxes for the surface water treatment plant. The remaining taxpayers have increased tax obligations of greater than 20%. Two of the three providers responsible for the largest reductions (the City of Kinston and the City of New Bern) experience greater than a 30% tax increase for any of the three options, making any of the options financially onerous for the taxpayers. Taxpayers in Onslow County would incur a minimum of a 20% tax increase for developing a new water sources. Taxpayers within Lenoir, Greene and western Pitt counties would incur the highest tax increases to replace the reduced Cretaceous pumping volumes.

County	Service Provider 2002	Aquifer	Total Reduction, gallons	% Change in Tax Burden for: Groundwater RO	New Well Field	New Water Treatment Plant
Up to 30% reductions						
Duplin						
	Chinquipin Water Association	Kbc	103,410,900	4	4	7
	Duplin County Regional Water	Kbc, Kucf	817,674,480	4	4	8
	Town of Beulaville	Kpd, Kbc	192,512,700	161	178	342
	Town of Greenevers	Kbc	65,700,657	80	89	170
Wayne						
	Wayne Water District Combined	Kbc, Kucf	1,952,087,400	5	5	10
	Fork Township Sanitary District	Kucf	530,686,800	7	8	15
Wilson						
	Town of Stantonsburg	Kucf	367,186,140	871	965	1853
Edgecombe						
	Conetoe Community Water Supply	Kucf	65,700,657			
	Town of Macclesfield	Kucf	65,700,657	130	144	276
	Town of Pinetops	Kucf	215,295,570	99	109	210
Martin						
	Town of Hamilton	Kucf	65,700,657	624	691	1328
	Town of Robersonville	Kucf	844,306,200	831	920	1767

Table 18. Hypothetical total reductions and percent changes per person, per year, in taxes by permitted water provider in declining water level zone, resulting from maximum reductions as mandated by the CCPCUA regulation.

County	ServiceProvider2002	Aquifer	Total Reduction, gallons	% Change in Tax Burden for: Groundwater RO	New Well Field	New Water Treatment Plant
Up to 75% reductions Pitt						
	Bell Arthur Water Corporation	Kucf	643076250	23	25	48
	Eastern Pines Water Corporation	Kpd, Kbc	927556250	15	17	32
	Greenville Utilities Commission	Kbc, Kucf	549580500	4	4	8
	Stokes Regional Water Corporation	Kucf	87986250	9	10	20
	Town of Ayden	Kbc, Kucf	259545250	116	129	248
	Town of Bethel	Kbc,Kucf	72916250	144	160	307
	Town of Farmville	Kbc, Kucf	717673313	56	62	119
	Town of Grifton	Kbc, Kucf	129185000	236	262	503
	Town of Winterville	Kbc, Kucf	225886380	31	34	65
Martin						
	Martin County Regional Water & Sewer Authority	Kbc, Kucf	223562500	6	7	14
	Town of Williamston	Kpd, Kbc, Kucf	492179813	71	79	151
Craven						
	City of New Bern	Kbc, Kucf	1937301250	38	42	80
	Craven County Water Department	Kbc, Kucf	1190988375	14	15	29
	Town of Dover	Kbc	45625456	771	853	1640

Table 19. Hypothetical total reductions and percent change per person, per year, in taxes by permitted water provider in dewatered or salt water encroachment water level zone, resulting from maximum reductions as mandated by the CCPCUA regulation.

A.3. Discussion and Limitations

A.3.1. C-1 Hydrology

Transmissivity is an important criteria, however, transmissivity trends are not straightforward. Transmissivity is mapped as a continuum for these analyses, when, in fact, transmissivity values in the Cretaceous of the Coastal Plain represent many discrete and discontinuous sand units which are mapped as a continuous surface for ease of analysis. The NCDEQ routinely tests a 10’ interval within the aquifer, which is not representative of the entire aquifer thickness. In addition, the CCPCUA does not contain sufficient monitoring wells throughout the 15-county area for robust interpolation.

Convention dictates that transmissivity increases with gross aquifer thickness (Spruill personal communication, 2017). This is reasonable, as transmissivity is a function of the hydraulic conductivity and the thickness of the aquifer, and this would be a justifiable approach if the aquifer was homogeneous and isotropic. However, the aquifers are not homogeneous, nor isotropic. Hydraulic conductivity, the rate at which an aquifer can transmit water is also called the coefficient of permeability and is dependent on the permeability of the medium through which the water is traveling. In the case of the CCPCUA, the permeability of the aquifer material varies. The Cretaceous aquifers, deposited in an alternating transgressive, regressive, near shore marine environment, are composed of fine to medium grained, glauconitic sands, bounded by marine silty mudstones and interbedded with silty limestones and mudstones (Winner and Coble, 1996). The Peedee is interpreted as a bioturbated open marine shelf environment. The Black Creek is representative of a near shore to deltaic environment. The Peedee is somewhat more continuous, with thicker sand bodies, whereas the Black Creek is composed of many small deposits of lenticular sands encased in a matrix of laminated sandy clays (Sohl and Christopher, 1983). The discontinuous nature of these types of deposits is responsible for the wide variations in the hydraulic conductivity and transmissivity, both vertically and horizontally.

The geophysical logs illustrate this intermittent and discontinuous sand deposition. Calculation of net sand to gross interval tallied from the gamma ray logs, illustrates the relative abundance of hydraulically conductive material in each aquifer. The Peedee averages 70% sand, with a range of values clustered from 55% to 82%. The R^2 value, or percent of variance explained, is small (0.2766), illustrating a correlation between the transmissivity and the net sand to gross aquifer ratio.

In an effort to understand and lend credibility the transmissivity trends in the Peedee and Black Creek aquifers, the net sand to gross aquifer relationships are investigated. The proposed relationship is based on the belief that an increase in the depositional interval does not increase the permeability and hence the transmissivity within that interval, unless there is a corresponding increase in the permeable material within that interval. Although each Cretaceous formation in the CCPCUA is composed of permeable sands and lesser permeable silts and shales, the aquifers are composed of randomly deposited and reworked sands. When the ratio of sands to encasing silty shale matrix remains the same or increases, the commonly held belief that transmissivity increases with increasing formation thickness remains viable. This holds true if the environment of deposition remains the same. Changing the environment of deposition into a bathyal and abyssal paleo-environment, will presumably diminish the ratio of gross sand to gross interval, with shales and mudstones dominating the lithology. At that point, it is expected that the permeable, potential aquifer material will also diminish, as will the formation’s transmissivity. Because no data is readily available to investigate the hydraulic conductivity or transmissivity of the bathyal, offshore, paleo-environment east of the CCPCUA, the relationships between transmissivity, aquifer thickness and hydraulic conductivity are tenuous.

There is insufficient evidence to refute or confirm the long-held belief of increasing transmissivity with increasing aquifer gross thickness. However, transmissivity likely increases with gross thickness not because the interval is thicker, but because there is a greater volume of sand within a larger interval. This allows more opportunity to encounter higher transmissivity sands.

The interpolation of the safe drawdown surfaces is also subject to interpretation. Safe drawdown is a function of the pre-pumping potentiometric surface estimated from the late nineteenth into the early twentieth century (Geise et al., 1997). The data are limited to driller's logs and notes for points throughout eastern North Carolina. Twenty points are available for the Peedee, with only 7 within the CCPCUA. Nineteen data points are available for the Black Creek, with 10 located within the CCPCUA.

The west side of the CCPCUA exhibits smaller safe drawdown, and therefore is more impacted by pumping changes than the east side of the CCPCUA. Although there is sizeable safe drawn available in the eastern portions the CCPCUA, much of it is saline and not considered economically viable, at this time. However, reclassification of the safe drawdown does not consider the salinity of the aquifers, as the economic viability of the aquifers will change with changing technological advancements. Therefore, the analysis of the safe drawdown only considers the vertical distance the potentiometric surface may be drawn down to without detrimental effects. Financial viability and potability are considered in the analysis of other criteria.

A.3.2. C-4 Available groundwater

Zone zero is the area on the west side of the CCPCUA where no usable aquifer exists. This area relies entirely on other groundwater sources, surface water or purchased water and is the most vulnerable area for water (in)security. It is also the area most economically and socially impacted by changes to the availability of potable water. Zone one encompasses an area in western Martin, Pitt, Greene, Lenoir and southwest Duplin counties. This is a small region with a thin aquifer. The communities within this area have an insecure source of groundwater and, like zone 0, are dependent on other water sources. Zone 2, the chloride transition zone has a stable source of treatable groundwater. However, because it is bounded on the east by high (>5,000 ppm) salinity groundwater, it is sensitive to salt water encroachment. Good management of these areas is vital to maintaining the potential viability of the Cretaceous aquifers. The aquifers in zone 3 have the full aquifer thickness with chloride values below 250 ppm. They are the areas which, in the past, have been overused and therefore need vigilant management. With prudent management the aquifers in the central region of the CCPCUA can provide a secure source of groundwater.

A.4.3. C-5 Alternate water sources, surface water

The lower 7Q10 values downstream are a function of how the USGS determines where to calculate values for surface waters. Only stream or river segments not influenced by winds or lunar tides have calculated 7Q10 values.

A.3.4. C-6 Financial capability

The financial ability to develop sufficient water resources is dependent on the financial impacts on communities with curtailed groundwater withdrawals. Economic cost for alternate water sources relies on statistics on the size and extent of service providers areas, the number of taxpayers within those areas, average income and taxes paid, tax rates, the volume of groundwater reduced (and subsequently needing replacement), and the price of the various investment alternatives. Ultimately, the tax increases each taxpayer must pay to replace the reduction in groundwater pumping volumes determines the economic responsibility carried by communities to protect the common groundwater resources. Equitable management considers how to fairly address problems of depletion within an economically feasible and justifiable framework. This issue is at the heart of the ecological and economic balance involved with equitably sustaining potable water supplies.

Not all sustainability problems can be resolved in monetary terms. Equally important, not all economic analyses can fully explain the gravity of environmental issues, yet the financial consequences are indicators of the burden communities must accept to deal with environmental concerns while continuing to provide for their citizens. Understanding that not all problems can be resolved in monetary terms and not all economic analyses can fully explain the gravity of environmental issues, financial consequences are indicators of the burden communities must accept to deal with environmental concerns while continuing to provide for their citizens. Not all communities have access to large surface water bodies or aquifer for new sources of water; only the bottled water option is available to all areas within the CCPCUA. However, for the purposes of the financial analysis, it is assumed that all communities within the CCPCUA have equal access to all of the alternative options. The ability to access alternate sources is previously considered.

The costs for groundwater RO operations from saline groundwater sources and the cost for a new well field are comparable. This is, in part, because the input water, and therefore the processing operations are very similar. The RO plant considered for this research is considered slightly (1,000–3,000 mg/L) to moderately (3,000-10,000 mg/L) saline (US Department of the Interior 1989). Sea water (>35,000 mg/L) desalination is not considered because, other than Onslow County, no coastal counties are subjected to the pumping reductions. The majority of the coastal counties do not produce from the Cretaceous aquifers, as they are either prohibitively deep or saline.

The construction of a water treatment plant is another viable option. It is interesting to note that two water providers, Martin County and the Neuse River Water and Sewer Authority (NRWASA) opted to invest in a costlier option to replace reduced pumping volumes with the construction of water treatment plants to treat surface water. It seems apparent that financial analyses were not the basis for determining the most viable option for new water supplies. Both facilities involved very large investments which commit these service providers to surface water sources for future needs. Although this is the more expensive alternative, the use of surface water is often viewed as a continuous and reliable source of water for the future.

The reduction volumes used for the analysis are based on the assumption that each permitted provider reduce only the maximum amount by the end of each phase. This does not actually reflect the historical timeline of when providers reduced their pumping. For example, the NRWASA was established in 2000 to meet regional water needs. The plant came on line in 2008 and met the mandated pumping reductions 8 years ahead of the phased reduction schedule.

The analysis shows that the majority of the providers who have less than a 20% increase in taxes to their taxpayers have a larger taxpayer base. This financial analysis assumes that each provider will fund their own water source projects. For future development this is an unrealistic assumption, as the size and population within a water providers area varies widely from approximately 20 for the Town of Hamilton to 78,000, for Onslow Water and Sewer Authority

(ONWASA). Large scale projects are not economically viable for smaller communities, yet in many cases they are proportionately subjected to the same rigorous reductions as larger communities. In 2016-2017, the Town of Hamilton, in Martin County had production from 2 wells in the Upper Cape Fear, with an annual permitted rate of 36,500,365 gallons per year and a reported average withdrawal of 12,585 gallons per day. Both wells are subject to the withdrawal reductions. In contrast, ONWASA produces from 41 wells from the Surficial, Castle Hayne, Beaufort, Peedee, and Black Creek aquifers and has an annual permitted rate of over a billion gallons per day (gpy) with a reported average withdrawal of 1,625,227 gpd, yet only 13 of the wells (Peedee and Black Creek) are subject to the CCPCUA mandated reductions. Whereas, ONWASA has several water sources and a much larger tax base (~$71 million in 2000), the Town of Hamilton only has an average of $16,000 from tax revenues. Although many smaller communities do currently have their own water sources, moving forward it might be more practical and economically feasible to join with other water providers to develop common alternate water sources and take advantage of the cost advantages that exist with larger water development and processing facilities. These “economies of scale” make the cost of larger water projects less expensive per unit (Zetland, 2011). Unfortunately, this option is not available or attractive to all water providers. Spatial barriers exist prohibiting many smaller water providers from taking advantage of the market power of trading water. Many of the smaller communities are spatially isolated and far from large treatment plants, aquifers or surficial water sources. Interconnects would entail long and costly pipelines, defeating the advantages of entering into cooperative agreements with larger providers.

Assessing the increased tax load to taxpayers is a viable method to discern an area’s ability to fund a project. However, neither of the two new water treatment plants was funded through taxpayer dollars. Funding for the projects came from grants and loans through the US Department of Agriculture, the Drinking Water State Revolving Fund, the Rural Center, the State of North Carolina, the US Environmental Protection Agency and local sources. In addition, the large expenditures were made possible through adaptive marketing partnerships and cooperative agreements between several water providers of various sizes. Ongoing operational and maintenance costs, as well as payments due on outstanding loans, paid for, in part, through the wholesale sale of water to neighboring communities and other member providers, not through taxpayer dollars.

Although key issues, the financial analysis does not address the true economic value, or the true economic pricing of water. In fact, the true cost of water includes the cost to develop water resources, as well as economic, social and environmental costs. Agricultural water use is also not considered in this analysis, as it is excluded from the CCPCUA reductions. Industries, to which no provider unit can be assigned (e.g. Patheon Inc. in Pitt County and Penco Products in Martin County), are also excluded from the analysis. While they do contribute to the tax base, they do not provide water outside of their plants, as such, they do not have a specific spatial footprint. They are, however, required to reduce withdrawals.

Several large water provider blocks, not covered in the analysis, are not displayed on the maps. They are either not subject to the CCPCUA pumping reductions because they are not pumping from the Cretaceous (as in the case of the easternmost coastal counties) or their primary source of water was already from alternate water sources. This is true of the majority of Edgecombe and Wilson counties, and the Town of Goldsboro in Wayne County, which source their water from the Tar or Neuse Rivers (Edgecombe County and the Town of Goldsboro). Wilson County pumps water from Contentnea Creek, reservoirs and lakes.

Aquifer storage and recovery, inter-basin transfer, the purchase of intra-basin finished water and banking projects are all viable options for replacing reduced pumping volumes, however, but not considered alternate sources for the purposes of this research, as they are methods for storing or moving previously developed water sources. In addition, because of the comparatively exorbitant cost of bottled water, it is not considered as a competitive option. It is surmised that if the public, who uses water through public utilities, paid the true cost of water, as opposed to the true value (the price they are willing to pay for it), water in Eastern North Carolina would be near limitless and in abundant supply. This assumption could change however under conditions of extreme environmental changes, or extreme drought.

Strictly comparing the costs, bottled water as an alternative option, is economically prohibitive and untenable. The least expensive bottled water sells for approximately $2.20 per gallon, or approximately 2,200 dollars per thousand gallons. Greenville Utilities, one of the largest utilities, water provider in eastern North Carolina charges approximately 4 dollars per thousand gallons. On a per gallon basis, consumers are willing to pay thousands more for bottled water than for community water as a source for drinking water. This disparity between the perceived and convenience value of bottled water and public water sources makes water resources management difficult and less than effective.

APPENDIX B: USING THE ANALYTIC HIERARCHY PROCESS TO WEIGH GROUNDWATER MANAGEMENT CRITERIA IN COASTAL REGIONS

The work conducted in this chapter has been submitted and accepted for publication in Elseviers's Coastal zone management: Global perspectives, regional processes, local processes. Editors: Mu. Ramkumar, R. Arthur James, David Menier, K. Kumaraswamy.

Abstract

Using freshwater resources in coastal regions to meet current societal demands without endangering the needs of future generations typically requires a reliance on management actions that are based on carefully chosen criteria. However, when it comes to managing coastal groundwater resources, it is not clear whether there is consensus among water professionals about (a) which criteria are the most important and, (b) how the degree of importance varies among criteria. In this study, the Analytic Hierarchy Process (AHP) is used to quantify the degree of importance of various groundwater management criteria by ascribing weights to the criteria.

The criteria that are considered in this study are hydrogeologic and aquifer characteristics, socioeconomic demands and needs of the study area, population dependent on groundwater resources, available groundwater supply, availability of alternate water sources, financial capability to develop alternate water resources, and political motivation and support to develop alternate water resources. A Likert-type survey was administered to 136 water professionals in various work sectors and locations across the United States to determine important criteria for managing groundwater. Results from the AHP reveal that water professionals perceived hydrogeologic and aquifer characteristics as the most important criteria for groundwater management with a weight of 28%, followed by the availability of groundwater sources with a weight of 19%. Socioeconomic demands and needs of the study area, population dependent on groundwater resources, available groundwater supply, and availability of alternate water sources were of intermediate importance with weights ranging from 11-16%. Financial capability to develop alternate water resources with a weight of 8% and political will with a weight of 5% were perceived to be the least important criteria. The results also reveal that there were no differences in perceptions of professionals from different work sectors or geographic locations. This study illustrates the usefulness of the AHP in managing groundwater resources in coastal regions.

B.1. Introduction

Sustainable use of potable water resources is imperative to global health (Gleick, 1998; Hunter et al., 2010; United Nations, 2007; World Health Organization, 2004). However, despite years of management interventions, use of many groundwater resources has become unsustainable due to overexploitation and contamination arising from human population growth, urban sprawl, industrial advancement, agricultural development, and climate change (Taylor et al., 2013; Hughes et al., 2011). Globally, population growth, low rates of groundwater recharge and high groundwater extractions have worked together to severely degrade water quality and diminish levels in groundwater reservoirs (Gleick, 1998; Rosegrant et al., 2002; Green et al., 2011; Cosgrove and Rijsberman, 2014). Although reversal of this trend is possible with management decisions that consider the multi-dimensions of groundwater, there is currently no consensus on the importance of various criteria for the sustainable use and equitable allocation of groundwater resources, particularly those in coastal regions.

The literature has shown how the perceptions of criteria for managing groundwater resources have evolved over time. For example, early philosophies for managing groundwater resources were based on the concept of ‘safe yield’ which was defined as the “limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve” (Lee, 1915). The definition of safe yield was later expanded to include economic considerations (Meinzer, 1923). Although these definitions focus on long term aquifer health, they were developed prior to sophisticated knowledge about aquifer drawdown, dewatering, and salt water intrusion (Conkling, 1946; Fetter, 1988; Schwartz and Zhang, 2003), processes that are important in coastal areas where large numbers of the world’s population reside.

Following Theis’ (1935; 1940) pioneering work on the analysis of aquifer characteristics, groundwater management criteria have proceeded to include the infringement on water rights (Banks, 1953), and the economic disadvantages and social impacts of pumping (Conkling, 1946; Freeze and Cherry, 1979). Other researchers have advocated for adoption of economic theories of optimization and exhaustible resources (Mays, 2013) and adaptive management (e.g., Gleeson et al., 2010; Klein et al., 2014) as viable strategies for implementing groundwater policy. Although authoritative bodies such as the Intergovernmental Panel on Climate Change (IPCC, 2014) and the United Nations (United Nations 1997) have stressed the importance of applying multi-criteria analysis and interdisciplinary research which incorporate qualitative and quantitative data from the natural and social sciences in studies of groundwater policy, it is still unclear how water professionals perceive and apply these criteria in their efforts to manage coastal groundwater resources. Understanding these perceptions is important because the choice of criteria and the assessment of the relative importance for those criteria are critical determinants to creating new and innovative management options (Hajkowicz and Collins, 2007; Chen et al., 2010) that would safeguard water resources for future generations.

Criteria on which groundwater management is based impact the efficient and sustainable use of groundwater, however, since not all criteria are of equal importance (Hajkowicz and Collins, 2007), it is not currently clear which criteria are the most important for managing groundwater resources. This research study seeks to evaluate the relative importance of these groundwater management criteria using the Analytic Hierarchy Process (AHP), a comparative weighting procedure increasingly being used to assess water resource planning (Calizaya et al., 2010; Cabrere et al., 2011; Panagopoulos et al., 2012; Li and Sun, 2017). In this research, AHP is used to assess how groundwater professionals perceive the importance of various criteria affecting groundwater management. Addressing this objective has implications for managing groundwater resources in coastal regions, especially when multiple criteria are considered. Coastal regions are particularly sensitive areas because these regions not only have large population centers, but they also harbor fragile ecosystems that are threatened by a myriad of coastal processes including saltwater intrusion and tropical storms. The use of the AHP in determining the relative importance of groundwater criteria is a novel application in groundwater research in coastal regions.

B.2. Methods

B.2.1. Establishing criteria for groundwater management

The criteria for assessing groundwater management are drawn from international guidelines that regulate the non-navigational use of water that were adopted by the International

Law Association (ILA) in 2004. Known as the Berlin Rules on Water Resources (ILA, 2004), these rules stipulate the relevant factors to be considered when determining equitable and reasonable use of water. The Berlin Rules were developed to refine the Helsinki Rules on the Uses of International Rivers (ILA, 1966; Salman, 2007), and the United Nations Convention on the Law of Non-Navigational Uses of International Watercourses (United Nations, 1997). The revisions account for changes in international environmental, international human rights, and the humanitarian law (ILA, 2004). In contrast to previous conventions, the Berlin Rules considered principles that specifically applied to groundwater. Thus, the Berlin Rules list nine factors that affect the equitable and reasonable use of groundwater resources. These factors served as a starting point for developing the seven pertinent groundwater management criteria that were appropriate for this study. The seven criteria that were borne out of the Berlin Rules are: (a) hydrogeologic and aquifer characteristics {i.e., attributes that influence that flow of water in the subsurface}, (b) socioeconomic demands and needs of a community, (c) the population dependent on groundwater resources in given area, (d) the volume of groundwater available in an aquifer at a given time, (e) availability of alternate water sources to develop, (f) financial capability of communities to develop alternate water resources, and (e) political motivation and support to develop alternate water resources

These criteria are particularly applicable to the study, as coastal zones have very specific policy challenges. Coastal regions face complex variations in aquifer characteristics (e.g. saltwater intrusion) due to the land sea interface; seasonal demands, needs and financial inputs; and coastal population clusters, often surrounded by rural communities, both of which require available and secure freshwater resources. In addition, global climate change will exacerbate a continual change to theses dynamic, interacting systems.

B.2.2. Survey instrument

To assure relevance to those who influence the strategic planning for water resources (i.e. water managers and water resource advisors), a survey instrument was designed to explore the perceptions of water professionals with respect to the seven groundwater management criteria as shown in Table 16. Survey questions targeted practicing water professionals working in different locations and work sectors.

Surveys were circulated using a random sampling approach via paper and online avenues. Paper copies of the surveys were dispensed during a professional water resource meeting held in the state of North Carolina in the United States in 2016. Approximately 50 people attended the meeting, during which 36 surveys were distributed, completed, collected and tabulated by the researchers. Additional surveys were administered online (n = 100), via the American Institute of Professional Geologists (AIPG) web portal. Information on the age range and experience of the respondents was not collected. The 136 responses represent an 8% margin of error, at the 95% confidence level (assuming a total population of 10000 people). Institutional review board approval was acquired prior to administering the surveys.

Code	Criteria
C1	Hydrogeologic/aquifer characteristics of the area of interest.
C2	Socioeconomic demands and needs of the community.
C3	Population dependent on the groundwater resources.
C4	Available groundwater volume to use for the population’s demands and needs.
C5	Availability of alternate water sources to develop for the population’s demands and needs.
C6	Financial resources to develop alternate water resources.
C7	Political motivation and support to develop alternate water resources.

Table 20. The seven groundwater management criteria used to explore the perceptions of water professionals.

The survey format consisted of carefully crafted questions that were worded to avoid ambiguity or confusion. The survey was designed to consider the seven criteria introduced in Table 16. These criteria were assessed via a standard, Likert-type survey, with responses on a scale of one through five (where 1 = not at all important, 2 = slightly important, 3 = moderately important, 4 = very important, and 5 = extremely important) (Likert, 1932). Typically, Likert type scales of 1-5 provide the respondents with answer sensitivity, indicating a relative strength of each response and avoiding extreme responses of agree or disagree. The 5-point scale is easy to understand and accurately captures respondents' opinions (Alharbi and Sayed, 2017) without diminishing response rate due to frustration (Babakus and Mangold, 1992). For each question, respondents were also given the opportunity to comment or elaborate on each question. Other information was collected to better understand the characteristics of the sample population.

The respondents of the survey were asked to identify (a) the location where they predominantly worked (i.e., in the United States and/or internationally), and (b) the sector in which they worked. The researchers later grouped the work locations in United States by the US census bureau regions (i.e., Northeast, Midwest, South and West). An answer of "National" indicates that the respondent worked in more than one US census region, whereas, "International" represents those respondents who worked in the United States and other countries outside of the United States or worked exclusively outside of the United States. An answer of "No response" indicates that the respondent did not identify the work sector. The work sectors that were identified included academia (identified as personnel from institutions of higher education), government agencies (which included federal, state, local or tribal agencies), industry, non-governmental/non-profit agencies or other. Respondents included 18 academics, 30 from government, 48 from industry, 5 from Non-Governmental Organizations (NGO) and 34 from other sectors. The majority of the “other” category was composed of professionals in the engineering and environmental consulting fields (hydrogeologic consulting-12, environmental consulting - 10, planning/permitting/inspection – 3, well field development – 2, retired – 2, oil, gas, minerals – 2, not specified – 2, elected official - 1). The “other” category is grouped together as an individual sector for the analysis. The participants responded voluntarily and received no compensation.

B.2.3. Analysis

A mixed methods approach was used to evaluate the survey results, as the responses were in the form of both qualitative and quantitative data (Creswell and Clark, 2007; Clark et al., 2008; Denzin and Lincoln, 2013). Likert-type results were analyzed as quantitative and ordinal data, the short responses (i.e., work location and sector) were considered quantitative and nominal data, whereas any additional comments were treated as qualitative data. Only surveys in which each criteria was assessed were used in the study. A lack of a response for a criteria was considered as one less response in the statistical analysis.

Basic descriptive statistics were generated in SPSS and R studio statistical software programs. The data that were acquired were ordinal and nominal, and not normally distributed. As a result, the assessed scores (in the case of the criteria analysis) have no relative difference between each value, and the mean was deemed inappropriate for analyses. Therefore, the Kruskal-Wallis test was used to explore if there were significant differences in how different groups of water professionals perceived the importance of the seven groundwater management criteria. The goal of this exercise was to determine if there was a difference between the perceptions of water professionals from different work sectors, and whether there were significant differences between the perceptions of water professionals from different locations at the 95% confidence level. The null hypothesis that was tested was that the medians of all variables were equal.

The scaled Likert-type data that were collected from the participant survey were converted to a ratio scale using the AHP to allow for a comparison of the intensity of each criteria. The AHP is useful for comparing different kinds of criteria (e.g., physical and social processes) and assigning priorities by using pairwise comparisons of criteria to assess the relationships between those criteria (Saaty, 1980; 1990; 2008; Saaty and Vargas, 1991). The comparisons were derived from the values acquired from the Likert-type survey and in this case, represent the relative perceptions of the water professionals regarding important groundwater management criteria. The AHP was used to develop criteria weights from paired comparisons by considering the relationships and variations in judgment between the multiple criteria from the many surveyed water professionals at the same time.

The protocol for determining weights of criteria is shown in Figure 76. The first step of this protocol involves choosing the criteria.

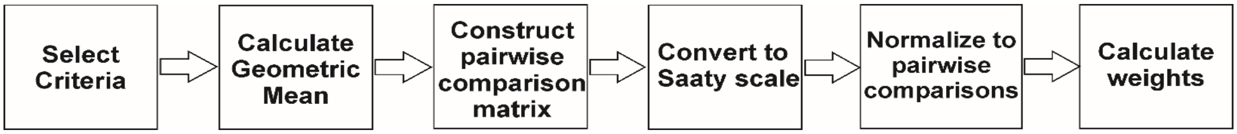

Figure 76. The protocol for assessing criteria weights utilizing the Analytic Hierarchy Process.

The authors deemed six criteria as important for effective groundwater management: 1) hydrogeologic characteristics, 2) demand, 3) population, 4) available groundwater, 5) availability of alternate water sources, and 6) financial ability to fund alternate water sources. Then, a Likert survey was administered to quantitatively determine how various stakeholders perceived the importance of the selected criteria. The geometric means from the scores of the Likert survey (expressed as a score between 1 and 5 on a scale of importance) were thereafter calculated and placed in a matrix. The first row and the first column in the resulting matrix comprised the headers. Since each header was a criteria that was identified by the authors, the resulting matrix was a 7 x 7 square matrix. Another matrix was then created by computing the ratio of the geometric means of scores of any two criteria (e.g., geometric mean of scores from criteria 1 to geometric mean of scores from criteria 2, geometric mean of scores from criteria 1 to geometric mean of scores from criteria 3, and so on and so forth). Therefore, each cell in the matrix was populated with a value that was based on the comparison between the raw Likert results for any two criteria.

The geometric means from the Likert survey were then converted to a 'Saaty intensity scale' (Saaty, 1980). The Saaty intensity scale (Table 17) represents the relative importance between any two criteria on a nine-point scale. Table 18 illustrates the relationships used to convert the Likert-type scale to the Saaty scale and shows the inverse relationships in the Saaty intensity scale. A value of 9 or 1/9 signifies that one criteria is nine times more important than the other. For example, if, for one criteria, the geometric mean from the scores of the Likert survey is equal to 1, then this value represents the largest possible difference between criteria, as the maximum possible score is 5 (i.e., 1/5). The value of 1 out of a possible score of 5, represents an "unquestionable support of the importance of one criteria over the other" and is therefore assessed a value of 9 or 1/9 on the Saaty scale (Saaty, 2008). This process converts a fixed scale, with no measurable distance between the scores, to one in which the criteria have measurable relative values to each other (Saaty, 2008).

Intensity of Importance	Definition	Description
1/1	Equal importance	Two Criteria are of equal importance
2, 1/2	Weak importance	
3, 1/3	Moderate importance	Moderate importance of one criteria over the other
4, 1/4	Moderate plus importance	
5, 1/5	Strong importance	Strong Importance of one criteria over the other
6, 1/6	Strong plus importance	
7, 1/7	Very strong importance	Very strong importance of one criteria over the other, evidence based
8, 1/8	Very, very strong importance	
9, 1/9	Extreme importance	Unquestionable or demonstrated support of the importance of one criteria over the other

Table 21. The fundamental scale of values representing the intensities of judgments between two groundwater management criteria (Saaty and Vargas, 2006).

Likert	Saaty
1/5 or 5/1	9 or 1/9
2/5 or 5/2	7 or 1/7
3/5 or 5/3	5 or 1/5
4/5 or 5/4	3 or 1/3
5/5	1

Table 22. The conversion of the Likert scale to the Saaty fundamental scale representing the intensities of judgments between two groundwater management criteria.

After a pairwise comparison matrix of the Likert data (Table 19) were converted to the Saaty Intensity Scale (Table 20), the pairwise comparison matrix was adjusted to create a normalized matrix (Table 21). This was performed by summing the values in each column of the matrix in Table 20 and dividing the values in each cell by the total of the column to yield normalized values (the sum of the normalized values in each column must equal one). The weights for the criteria are then determined by computing the average values from each row that represents a criteria in the normalized matrix (Table 21).

	C1	C2	C3	C4	C5	C6	C7
C1	1.00	0.82	0.87	0.91	0.82	0.76	0.67
C2	1.22	1.00	1.05	1.11	1.00	0.92	0.81
C3	1.15	0.95	1.00	1.05	0.95	0.87	0.77
C4	1.10	0.90	0.95	1.00	0.90	0.83	0.73
C5	1.22	1.00	1.05	1.11	1.00	0.92	0.81
C6	1.32	1.09	1.15	1.21	1.09	1.00	0.88
C7	1.50	1.23	1.30	1.37	1.23	1.13	1.00

Table 23. Pairwise comparison matrix of the seven water management criteria using scores from a 5-point Likert scale.

	C1	C2	C3	C4	C5	C6	C7
C1	1	3	2	2	3	2	4
C2	1/3	1	1	1/2	1	2	3
C3	1/2	1	1	1	2	2	3
C4	1/2	2	1	1	2	3	4
C5	1/3	1	1/2	1/2	1	2	3
C6	1/2	1/2	1/2	1/3	1/2	1	2
C7	1/4	1/3	1/3	1/4	1/3	1/2	1

Table 24. Pairwise comparison matrix converted to a Saaty fundamental scale.

	C1	C2	C3	C4	C5	C6	C7	Weight
C1	0.29	0.34	0.32	0.36	0.31	0.16	0.20	0.28
C2	0.10	0.11	0.16	0.09	0.10	0.16	0.15	0.12
C3	0.15	0.11	0.16	0.18	0.20	0.16	0.15	0.16
C4	0.15	0.23	0.16	0.18	0.20	0.24	0.20	0.19
C5	0.10	0.11	0.08	0.09	0.10	0.16	0.15	0.11
C6	0.15	0.06	0.08	0.06	0.05	0.08	0.10	0.08
C7	0.07	0.04	0.05	0.04	0.03	0.04	0.05	0.05

Table 25. Normalized pairwise comparison matrix of the seven groundwater management criteria on a Saaty fundamental scale.

Note that judgement scoring in the pairwise comparison is not always consistent (Saaty, 1980; Saaty, 1990; Saaty and Vargas, 1991; Saaty and Vargas, 2006; Saaty, 2008; Chen et al., 2010). Therefore, prior to accepting the weights, a degree of consistency or a Consistency Ratio was determined by computing the ratio of a Consistency Index (CI) to a Random Consistency Index (RI). This check assures that the subjective score from the Likert survey and the associated Saaty comparisons are consistent.

The CI indicates the consistency of judgement in the pairwise matrix and is given by:

$$CI = (\lambda - n)/(n - 1) \qquad (Eq.1)$$

where λ is the product of the reciprocal of the normalized values for each criteria in the matrix and the average of each row in the matrix (Saaty, 1990), and n is the number of criteria. The RI is a randomly generated pairwise comparison matrix using the same 1-9 relative importance scale of a sample of 500 randomly generated matrices (Saaty, 1990). A ratio of less than 0.1 indicates a satisfactory degree of consistency, allowing for the computed weights to be accepted (Saaty, 1990). The reader is referred to Saaty (1990) for a complete description of the method as well as the RI reference table used in the process.

B.3. Results and discussion

As accessible potable water resources become threatened in coastal regions, adequate and accurate decision-making methods are needed to develop strong, equitable and effective groundwater management strategies. Consideration of the many criteria involved with water management has proven to be a successful, integrative and comprehensive tool that respects the myriad of physical and socio-economic dimensions of water management and yields well informed and enforceable strategies adaptable to the long-term sustainability of aquifers (Hajkowicz and Collins, 2007; Hajkowicz and Higgins, 2008). However, it has been unclear how to best assess weights to criteria and whether there is consensus among water professionals about which criteria are the most important for managing groundwater and, how the degree of importance varies among these criteria.

The results from the survey that queried water professionals regarding their perception about the relative importance of seven physical and socioeconomic criteria that impact how groundwater is managed and allocated indicate that responses pertaining to all the criteria, excluding political will, had median scores of 4 or 5 on a Likert scale (Table 22). These results illustrate that water professionals valued all of the criteria (excluding political will) as either important or extremely important.

	C1 Hydrogeologic and Aquifer Characteristics	C2 Socioeconomic Demands and Needs	C3 Population	C4 Available Groundwater	C5 Alternate Sources	C6 Financial Capability	C7 Political Will
Geometric Mean	4.5	3.7	3.9	4.1	3.7	3.4	3
Median	5	4	4	5	4	4	3
Mode	5	4	5	5	4	4	3
Variance	0.67	0.9	0.9	0.87	1.08	0.95	1.48

Table 26. Summary statistics illustrating the relative importance of the groundwater management criteria.

Of all the criteria, hydrogeologic and aquifer characteristics (C1), and the available groundwater volume (C4) were perceived by the participants to have been extremely important with median scores that were equal to 5 on the Likert scale. In contrast, political will (C7) had a lower median score of 3 on the Likert scale suggesting that the survey participants perceived this criteria to be moderately important.

Socioeconomic demands and needs (C2), population (C3), alternate water sources (C5) and financial capability (C6) had median scores of 4 (very important) on the Likert scale. For completeness, and as an illustration of how the descriptive statistics compare to each other, the geometric mean, median, mode and variance are included in Table 22. The geometric mean and the mode align with the patterns displayed by the medians (the statistics for hydrogeologic and aquifer characteristics (C1) and the available groundwater volume (C4) are generally higher than the statistics for the other criteria). Although viewed as a confirmation of the validity of the criteria choices, the raw Likert scores give little indication of the relative importance of the criteria, and the data do not allow for direct and quantifiable comparisons of criteria. The results from the AHP (see below) resolve this issue.

The respondents to the questionnaire indicated that their primary work responsibilities were in 46 states of the United States and 22 other countries. For the respondents who primarily worked in the United States, approximately 12% worked in the Northeast, 16% in the Midwest, 23% in the west and 49% in the South. Results from the Kruskal-Wallis test reveal that there were no significant differences in the perceptions of water professionals from different geographic locations (Figure 77). This result suggests that there was general agreement about the level of importance for groundwater management criteria regardless of geographic location.

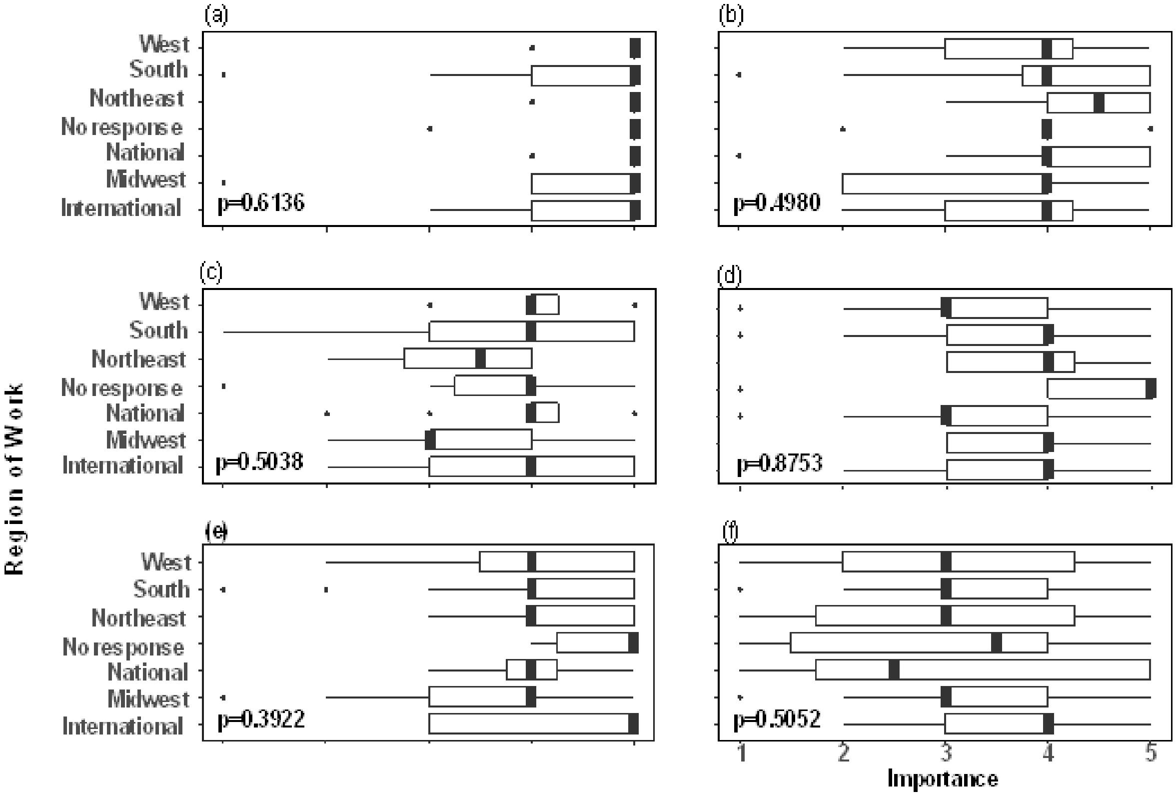

Figure 77. Box plots illustrating how groundwater professionals perceived the importance of Criteria 1-6 by location (a) C1: hydrogeologic and aquifer characteristics, (b) C2: socio-economic demands and needs, (c) C3: population dependent on the groundwater resources, (d) C4: available groundwater volume, (e) C5: availability of alternate water sources, (f) C6: financial resources. Thick vertical lines in each box plot represent the median. The dots represent the outliers, or those points falling outside of the upper and lower quartiles of the data.

Approximately 4% of the respondents self-identified their work sector as non-governmental organization/non-profit, 13% as academic, 22% as government, 36% as industry, and 25% as “other”. The results indicate that there is little variation in the distribution of responses from groundwater professionals to all criteria based on work sector. Comparable to the results from the responses about various work locations, the results from the Kruskal-Wallis test of significance reveal that there were no significant differences in the perceptions of water professionals from different work sectors (Figure 78). This result suggests that there was general agreement about the level of importance for groundwater management criteria regardless of the sector in which the respondents work.

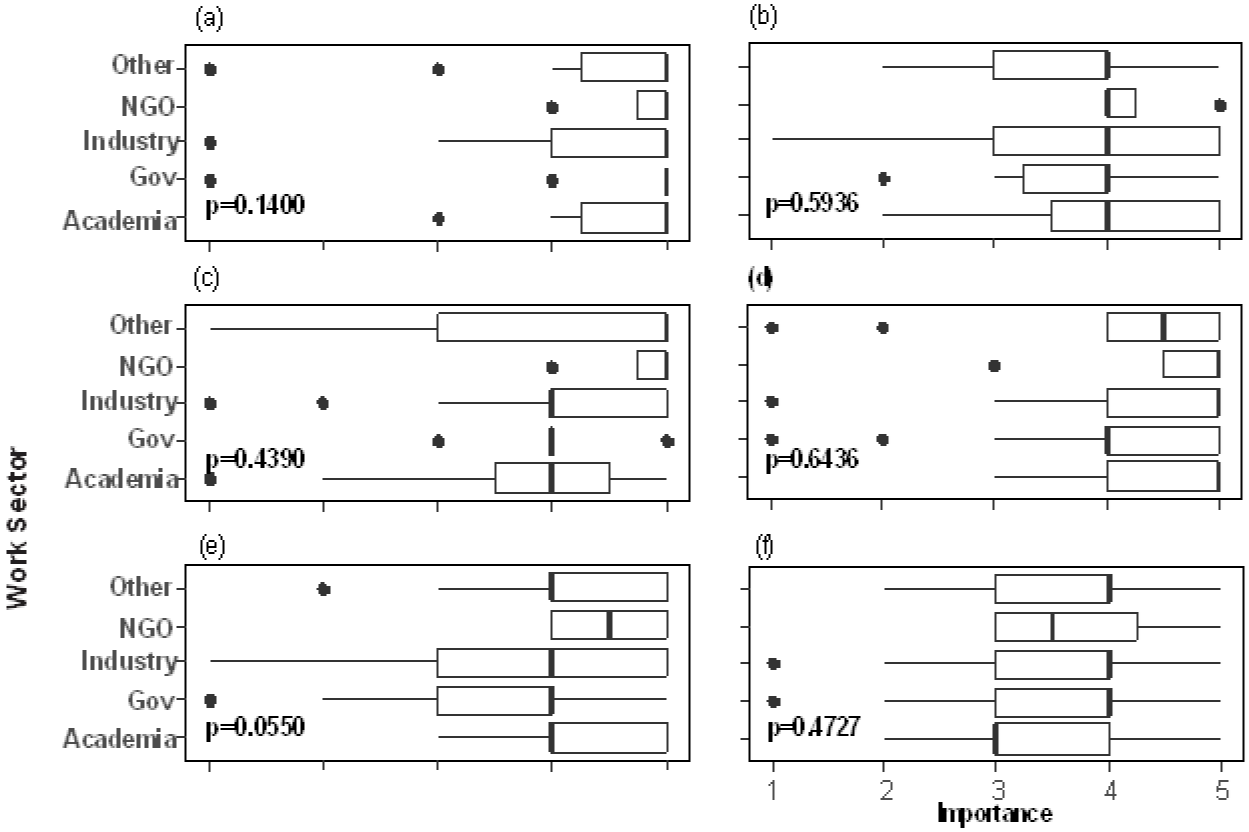

Figure 78. Box plots illustrating the variations of groundwater professional's perceptions to Criteria 1-7, by work sector (i.e. Other, NGO (Non-Governmental Agency or Non-Profit), Industry, Gov (Governmental Agency), and Academia). (a) C1: Hydrogeologic and aquifer characteristics, (b) C2: socio-economic demands and needs, (c) C3: population dependent on the groundwater resources, (d) C4: available groundwater volume, (e) C5: availability of alternate water resources, and (f) C6: financial resources.

As shown in the boxplots (Figures 77 and 78), there is very little difference in the responses from either group, illustrating that water professionals from different locales and work sectors have a common perception of important groundwater management criteria. In all cases, the p value is greater than 0.05, indicating weak evidence against the null hypothesis. These results suggest that, because neither the location (Figure 77), nor work sector (Figure 78) impacted the answers of the water professionals as to the importance of the various criteria, the criteria chosen, seem to be of universal importance among the sample population.

A check of the Consistency ratio following the creation of a matrix with the Saaty (1980) intensity scale shows that the comparison judgements are consistent, as the computed ratio is

0.03. The judgments are consistent because the research was designed to avoid requiring the water professionals make direct comparisons of criteria. Allowing water professionals to make direct comparisons of criteria would have resulted in inconsistent comparisons, as judgements by different individuals would likely have resulted in different weight values. The average values that represent the weights of all the criteria are therefore acceptable because the Consistency ratio is less than 0.1.

The Likert-type survey was originally employed to prevent the water professionals from having to directly assess weights to the criteria. Having water professionals directly assess weights has proven to be biased and unreliable (Goldstein, 1990; Hajkowicz and Higgins, 2008; Korhonen et al., 2013) and often giving inaccurate and misleading results (Rowe and Pierce, 1982). Using the AHP, the authors used the geometric means from Likert surveys to compute the importance of each criteria and how each criteria compares to other criteria. As such, the researchers assigned larger weights to the more important criteria as determined through the AHP.

The weights that were derived through the AHP (Table 23) were compared to the weights acquired from two traditional techniques to determine how well the AHP performed in establishing weights for groundwater management criteria (Table 24).

	C1	C2	C3	C4	C5	C6	C7	Weight
C1	0.29	0.34	0.32	0.36	0.31	0.16	0.2	0.28
C2	0.1	0.11	0.16	0.09	0.1	0.16	0.15	0.12
C3	0.15	0.11	0.16	0.18	0.2	0.16	0.15	0.16
C4	0.15	0.23	0.16	0.18	0.2	0.24	0.2	0.19
C5	0.1	0.11	0.08	0.09	0.1	0.16	0.15	0.11
C6	0.15	0.06	0.08	0.06	0.05	0.08	0.1	0.08

Table 27. Normalized pairwise comparison matrix of the seven groundwater management criteria on a Saaty fundamental scale.

Criteria	Median Ranking	Simple Ratio	AHP
C1	1	16.64	28.16
C2	3	13.98	12.43
C3	3	14.63	15.86
C4	1	15.73	19.33
C5	3	14.12	11.3
C6	3	12.96	8.18
C7	7	11.94	4.75

Table 28. Comparison weights from AHP and traditional techniques.

The traditional techniques are (a) a ranking based on median scores from Likert surveys, and (b) a simple ratio of the sum of scores for each criteria to the sum of all criteria scores from Likert surveys. Had a ranking approach based on median scores from Likert surveys been used, the rankings would have revealed that hydrogeologic and aquifer characteristics (C1) and available groundwater (C4) would have had the highest ranking, with social and economic demands and needs (C2), population (C3), availability of alternate water sources (C5) and financial capability (C6) being of intermediate ranking. Political will (C7) would have had the lowest ranking. Had the traditional simple ratio method been used, the weights would have had little variation in the ranges (between 11 and 17). However, when the AHP is used, the hydrogeologic and aquifer characteristics criteria (C1) is perceived to be the most important, followed by available groundwater (C4), population (C3), socio-economic demands and needs (C2), alternate water sources (C5), financial capability (C6), and political will (C7), respectively (Table 24). Although the relative importance of the criteria (i.e., rankings) is the same with the simple ratio method and the AHP, the AHP reveals that the hydrogeologic and aquifer characteristics criteria has a weight of approximately 1.5 times more than the criteria with the next largest weight (available groundwater (C4) and approximately 6 times the weight of the criteria with the least weight (political will (C7) (Table 24). These characteristics are not evident in the ranking and simple ratio techniques.

Political will was perceived to be of low importance, yet, 26% of those who responded with “optional” comments mentioned regulatory or political concerns. Although this may indicate the respondents’ recognition of a need for, and difficulty of working within the constraints of the political system, there appears to be a disdain for the importance of political will, and an unwillingness to accept the relevance of political will to groundwater management. For example, a respondent from the west stated that there is no real political will, including that of the Governor of the US state of California, to provide other sources for drinking water resources (e.g., desalination). The respondent reasoned that this was an economic decision based solely on costs for construction and maintenance. Furthermore, the respondent added that either water agencies or the “first users” own all groundwater in California, and the courts have ruled that the State cannot regulate the consumptive use by the "first users", inferring that the political authorities are either unwilling or unable to affect change. Despite such comments that highlight the structural rigidities of groundwater management, it is interesting that water professionals, regardless of location, placed a low importance on political will.

Regulatory framework, existing legislation and regulations weighed heavily with water professionals, especially those in the west and the Northeast. Many mentioned the futility of changing the existing regulatory structure or previous ownership claims. “Who claimed ownership first? Who has legal access to the resource? Do the current owner’s use impact other current users’ abilities to use the resource? Does the new proposed use impact current users’ abilities to use the resource?” “Can management work within existing laws and regulations or are changes required? If the latter, are such changes politically feasible?” It is interesting to note that although the respondents highlighted several structural impediments to managing groundwater, the water professionals highly valued hydrogeologic and aquifer characteristics (C1) as the most important factor to consider when evaluating water management strategies (weight = 28.16%), with political will (C7) as the least important consideration (weight = 4.75%) (Tables 22 and 24).

The criteria and associated weights used in this study should not be considered as rigid constructs to be used across all spatial and temporal scales but as guidelines for groundwater management assessments that are particularly applicable when considering environmental changes as well as responses of humans to those changes (e.g., adaptation to environmental change, subsidence, threats from saltwater intrusion etc.). Thus, the criteria and weights presented in this study may change depending on who uses water, what the water is used for, and time periods over which water management issues are to be considered. This is because water demands fluctuate with changes in ecological (e.g. as a consequence of climate change), political, regulatory, religious, cultural, and technological aspects of water use (Gleick, 1998).

The data from the survey represents an incomplete picture of important groundwater management criteria. There was agreement across work sectors and work locales that minimized the importance of political will. This common disregard for the necessities of working within the political system may be a hindrance to developing new management approaches that need to be promoted and funded by political entities. The surveyed water professionals ostensibly have difficulty in seeing beyond their own disciplines and fields of interest, with an apparent disconnect between political realities and the belief that hydrology is by far the most important consideration in crafting management schemes. This result has important implications for consensus on aquifer management. On regional scales, water professionals are likely to agree on large scale strategies. Agreement on the importance of each criteria may encourage professionals to view management on an aquifer-wide scale, crossing geopolitical boundaries, with considerations of the unique hydrogeologic problems facing coastal systems, thereby crafting “big picture” approaches. Perhaps the charge for water professionals is the establishment of the vision, creation of performance standards, establishment of monitoring networks and the creation of specific hydrogeologic tactics to manage the aquifers. However, because the water professionals do not acknowledge the importance of political will, daily management, coordination and oversight might be most effective if left on a local stakeholder scale. The reality is that sustainable management strategies in coastal regions are developed and moved forward through political will, for without political support, funding, permits and supporting management infrastructure are difficult, if not impossible to obtain or maintain. Until water professionals understand and reconcile the multi-dimensional nature of water management, the hydrogeologic issues in coastal regions will be difficult to tackle (Kay and Adler, 2005).

B.4. Shortcomings

Likert-type scaled surveys are typically employed to explore attitudes and perceptions (Likert, 1932; Dittrich et al., 2007). The respondents answer a series of questions in which they provide their perceptions of the relative strength of importance to various statements, and although it is a common method to ascertain attitudinal information, there is no quantitative measure of the difference between respondents’ answers. The Likert-type scale was employed to allow respondents to assess their perception of each criteria without regard for the other criteria. As such, the importance of one criteria did not diminish the importance of the others.

The criteria introduced in this research study are intended as a preliminary position for management discussions but are not intended to constitute an exclusive list. Other criteria suggested by respondents included water budgets, available infrastructure, competing current and future uses, ownership, quality and treatment, conservation, sustainability, water rights and impacts to ecology. These are important considerations in coastal regions. In this study, omission of criteria that may be deemed important for sustainability by other water professionals does not necessarily lessen the importance of any other criteria. Because each criteria was scored independently, the resulting scores did not influence the impressions of the respondents toward the importance of other criteria. (Hajkowicz and Higgins, 2008). For example, a score of 5 (extremely important) on one criteria, does not negate the importance of another criteria. It should be noted however, that if new criteria were added to the list presented in this study, then the relative weights of the criteria that were computed herein would change. It is recommended that this be considered if researchers are to include additional criteria to the ones suggested in this paper.

B.5. Conclusions

The novelty and value of this research study are that it addresses questions about how groundwater management criteria in coastal regions should be analyzed, how the perceptions vary by water professionals, and how the degree of importance varies among the criteria. The use of the AHP in establishing weights of groundwater management criteria is also a novel contribution. Although the results of the study reveal that that the respondents to the survey perceived hydrogeologic and aquifer characteristics, as well as the available groundwater volume in the area of interest to be of the highest importance, it is important to note that the hydrogeologic and aquifer characteristics were 1.5 times as important as the available groundwater volume. Here, political will was perceived to have the least importance although many respondents commented on its relevance and implications.

Coastal regions are complex and interconnected, creating groundwater concerns most effectively managed when strategies are adapted to the appropriate spatial and temporal scales.

Groundwater issues impacting the local coastline areas are different than those issues viewed at a more regional scale. The results of the survey of water professionals highlight the need for management on the various scales. Those surveyed represent professionals working on different scales. They also represent professionals working domestically and internationally. When given a common set of criteria for managing groundwater, water professionals agree on the most and least important criteria. The results also show that the perceptions of water professionals concerning the importance of groundwater management criteria were similar across work sector and work locale.

The focus on hydrogeologic criteria and downplaying of socio-political criteria may be a function of the demographics of the respondents. Largely, the water professionals who were surveyed in this study consisted of geologists and engineers. Missing from this study are other stakeholders such as mayors, council members, financial officers and other decision makers whose responsibilities it is to improve, update or expand existing water sources for coastal communities. Thus, future studies might involve a comparison of the perceptions of water professionals with other stakeholder groups. For example, water purveyors and members of water boards could contribute ideas on data sharing and the willingness to participate in collaborative projects. Also, end-users could be surveyed to unravel their interest and willingness to take part in conservation measures that minimize how much water is used during various water consumption activities. It is envisioned that multidimensional, mixed method approaches such as the AHP and the textual analysis presented in this paper will contribute to the sustainable use of coastal groundwater resources to meet current and future demands of water by providing means for various stakeholders to focus on the most important criteria for groundwater management.

APPENDIX C: GAGING GROUNDWATER MANAGEMENT: USING GROUNDWATER STORAGE VOLUMES TO ASSESS AQUIFER SUSTAINABILITY IN NORTH CAROLINA COASTAL PLAIN, USA

Abstract

A serious global concern for groundwater managers is how to adequately evaluate the condition and sustainably of aquifer systems. Recognizing the changes in aquifer conditions is difficult, because data are often spatially or temporally limited. This research proposes a new perspective that uses existing water level data of wells and augments it with a volumetric storage assessment. This approach uses geospatial techniques to analyze changes in aquifer storage volumes and provides a three dimensional analysis of how the larger aquifer system has changed over time. Using the Central Coastal Plain Capacity Use Area in eastern, North Carolina, U.S.A. as a case study, the research explores the effectiveness of this new integrative approach. Over the period from 1900 to 2002, groundwater volumes declined by 2.2% in the Black Creek, Cretaceous aquifer. The regulatory intervention included mandated pumping reductions and resulted in rebounding water levels. Changes in the storage volumes for the years 2002 to 2015 confirm the positive effects of the mandated reductions. Although the results from both gages (water levels and storage volumes) agree that there were changes in aquifer conditions prior to and following the regulation, the two approaches indicate different magnitudes of change. The discussion section explores if changes in water levels are an accurate indication of the overall aquifer conditions and responses of aquifers. This research suggests the importance of an additional tool for water managers to use to quantitatively gage and adapt to changing aquifer conditions.

Key points

- Augments water level data with volumetric storage assessment for evaluation of aquifer sustainability
- Quantitative gage of changing aquifer conditions
- Compares calculated changes in water levels to changes in groundwater storage volumes

C.1. Introduction

Globally, high rates of groundwater extractions have resulted from population growth coupled with low rates of groundwater recharge and caused severe degradation of groundwater resources (e.g., Heath and Spruill, 2003; Anisfeld, 2010, Gleeson et al., 2011; Nelson, 2012). This scenario has forced water managers to choose among a variety of strategies to sustainably manage the resource (Klein et al., 2014). For managers, assessing and sustaining groundwater resources is a difficult balance between meeting present day demands while planning for tomorrow's needs. Frequently, management decisions are a reaction to a crisis, after a quality or quantity problem occurs, and by the time the problem becomes evident, the problem becomes much more difficult to remedy. Rather than wait until the problem becomes unmanageable, water managers can monitor groundwater levels thereby anticipating and avoiding future problems.

Typically, management strategies are based on the best hydrogeologic information available from well monitoring programs. The well tests and water level data reflect local variations of observed characteristics and conditions which are then applied to a larger, more regional scale. This article expands on this approach by using geospatial techniques to quantify changes in groundwater storage volumes derived from groundwater level data. The novelty of this research is that changes in groundwater volumes are calculated from water level data and are used to assess the effectiveness of groundwater management strategies.

Strategic management of degrading aquifers in eastern North Carolina (USA) became imperative after a severe imbalance occurred between withdrawal and recharge rates resulted in declining water levels (as much as 2.4 m per year), large cones of depression (i.e., regions where groundwater levels are significantly depressed around a well due to groundwater pumping), saltwater intrusion, and low well yields in the Cretaceous age aquifers (Giese et al., 1997; Heath and Spruill, 2003; Lautier, 2006). To ameliorate this growing problem and maintain beneficial use of groundwater resources, the state of North Carolina developed an aggressive water policy by creating the Central Coastal Plain Capacity Use Area (henceforth the Capacity Use Area or CCPCUA). The regulation, based on observed changes to water levels throughout a 15 county area in eastern North Carolina (Figure 79), mandated tiered pumping reductions and permitting. This research assesses the success of the Capacity Use Area by evaluating how groundwater storage volumes have changed over time as the aquifers experience groundwater withdrawals and/or recharge.

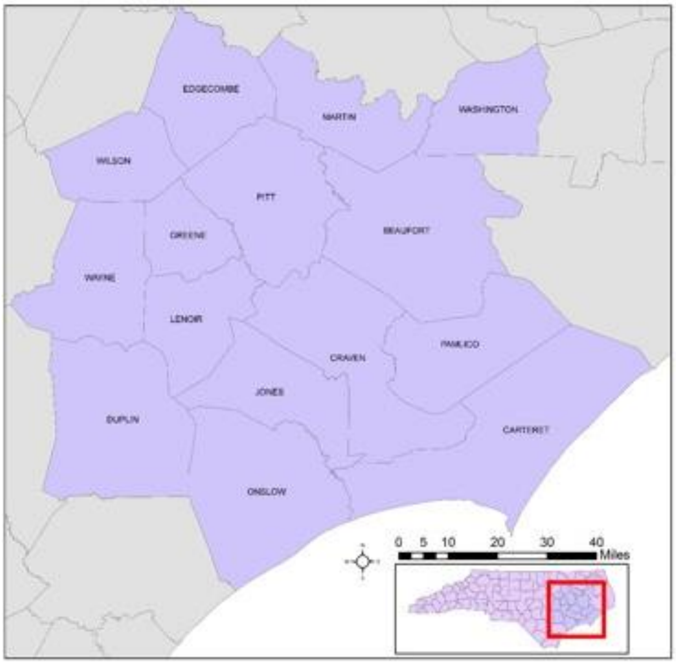

Figure 79. Fifteen Coastal Plain counties of the CCPCUA, NC.

C.1.1. Research objectives and goals

The objective of this study is to illustrate how augmenting water level data with aquifer storage estimates improves aquifer assessment and subsequent groundwater management. This is achieved by studying the change in groundwater storage of the Black Creek, Cretaceous aquifer in eastern North Carolina (USA). The overarching goal is to develop a tool using readily available data to quantitative gage changing aquifer conditions.

C.1.2. Significance

Water level monitoring is a common groundwater management tool used to observe changes in aquifers over time. Changes in water levels are used as indicators of the sustainability of the aquifer system and the availability for continued groundwater use at discrete locations. Combined with an analysis of storage volumes, water level monitoring can provide a picture of the condition of the larger aquifer system. This case study is applicable on local and regional scales and serves as an example for water managers on best practices for ongoing assessments of water resources. It is a useful example of how to accurately evaluate changes within the aquifer system. Through a thorough understanding of the larger system groundwater managers can create refine and adapt management strategies to changing aquifer conditions.

C.1.3. Study area

Until the early 21st century the growing population was predominantly dependent on high quality groundwater obtained from a series of Cretaceous aquifers. However, by the end of the 20th century, the groundwater withdrawals exceeded the groundwater recharge, and, consequently, water availability in the region became threatened. In 2002, the area was designated as a Capacity Use Area with state mandated withdrawal permits, registrations and, depending on local aquifer conditions, between 30 to 75% groundwater pumping reductions.

C.2. Methodology

Changes in groundwater storage volumes in the Black Creek, Cretaceous aquifer in eastern North Carolina are evaluated over the period from 1900 until 2015. This period covers the years prior to and after the introduction of the CCPCUA regulation. Water level and potentiometric surface data obtained from the North Carolina Department of Environmental Quality (NCDEQ) and the United States Geological Survey (USGS) are used to provide estimates of groundwater volumes for the years 1900, 2002, 2008 and 2015. These years represent instances in time when the aquifer was impacted by different conditions that were imposed through different management strategies. The year 1900 represents the first year on record that the USGS had monitoring data with which to draw potentiometric maps (Giese et al., 1997). This year serves as the baseline for predevelopment water levels. The Capacity Use Area was enacted in 2002 and thus 2002 represents the year after significant groundwater withdrawals, but prior to reductions. It is assumed that 2002 represents the year in which groundwater levels were at their lowest over the period of record. The first phase of the groundwater reductions was completed by 2008. Under the CCPCUA regulation, by 2008 withdrawals of greater than 100,000 gallons of water per day were required to be reduced by 10% to 25%, based on one of the three aquifer conditions: 1) dewatering, 2) salt water encroachment or 3) water level declines exceeding recharge rates. By the year 2008, water levels are anticipated to show some stabilization or recovery. The year 2015 reflects the completion of Phase II reductions of 20% to 50%.

Only the Black Creek aquifer is chosen for analysis in this study. This aquifer has adequate data for analysis, as it is the Cretaceous aquifer that has the most extensive groundwater level and aquifer property data. For completeness, groundwater levels from individual monitoring wells are included in the evaluation of the effectiveness of the groundwater management strategies. A description of how the groundwater level data are processes is included in the following section.

C.2.1. Water level analysis

Water level data acquired from NCDEQ are used to calculate recovery rates for groundwater levels in the Black Creek (15 wells) aquifer. The wells chosen for the analysis were constructed prior to the inception of the CCPCUA and have at least a 10-year water level history of at least 3 measurements per year. Groundwater level recovery is calculated for each of five periods ((a) 1900 – 2015, (b) 1900 - 2002, (c) 2002 - 2008, (d) 2008 - 2015, and (e) 2002 – 2015) using:

$$r = \frac{(h_2 - h_1) * 100}{\mathbf{s}a} \qquad \text{(Eq. 7)}$$

Where,

R is the percent recovery
h_2 is the water level for time period 2
h_1 is the water level for time period 1
sa is the available drawdown in 1900

For each of the aforementioned time periods, mean groundwater level for the last year of the period is determined. Pre-development potentiometric surface maps for the Black Creek aquifer is constructed and water level values for the chosen analysis locations are recorded. To obtain the change in the water levels from time 1 (h_1) to time 2 (h_2), the earlier recorded mean water level (h_1) is subtracted from the mean water level for the more current time period (h_2). The change in water level (h_2- h_1) is normalized by dividing the water level change by the vertical distance between the average water level in 1900 (as determined by the elevation of the potentiometric surface) and the base of the aquifer, herein referred to as the available drawdown.

C.2.2. Storage analysis

The methodology used to determine changes in groundwater volumes stored in the Black Creek aquifer in the CCPCUA is similar to that used by McGuire (2001, 2003, 2004, 2007, 2009, and 2011) and McGuire et al. (2003) to estimate groundwater depletion in the unconfined High Plains aquifer. McGuire et al. (2001, 2003, 2004, 2007, 2009, 2011) used water level changes and statewide, storage characteristics to estimate water volumes from a predevelopment baseline. For the purposes of the current research, the storage calculations, the aquifer in the study area was divided into the confined and unconfined portions of the aquifer.

The protocol for assessing changes to water volumes stored in aquifers involves acquiring a series of potentiometric surface maps for the Black Creek aquifer, obtained from the NCDEQ. These data are displayed and analyzed using the ESRI ArcGIS 10.3 software. Groundwater storage volumes are calculated using the mean water levels for each calendar year. The storage volume analysis is performed for the same time periods as the water level analysis to evaluate differences in the two aquifer assessment approaches.

Structure contour maps representing the aquifer top and base for the Black Creek aquifer is created with data sourced from the NCDEQ (http://www.ncwater.org) and a private hydrogeologic and engineering consulting firm. The potentiometric surface maps, used in conjunction with the structure contour maps, establish the dewatered, the unconfined, and the “economically usable” (<5,000 ppm) confined portion of the Black Creek aquifer system. Salinity values, acquired from the NCDEQ, are interpolated to define the economically usable portion of the aquifer. The 5,000 ppm chloride line is chosen as the “economic” boundary as groundwater reverse osmosis (RO) treatment plants typically process water with salinity values of less than 5,000 ppm chloride (personal communication T. Seacord, Carolla Engineering). In addition, wells with greater than 5,000 ppm chloride are not subject to the CCPCUA reductions, as they are rarely used for potable water. Groundwater volumes are calculated separately for the confined and unconfined portions of the aquifer (Figure 80). For the purposes of this study, the area of interest was limited to the CCPCUA counties.

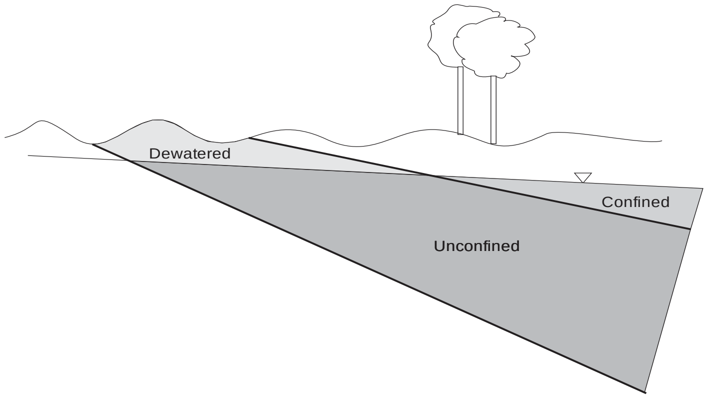

Figure 80. Schematic of the confined and dewatered portions of a theoretical aquifer.

The cut and fill tool in ArcGIS is used to compute the available storage volumes in the confined, unconfined and dewatered zones at various points in time. The volumes between the respective surfaces are multiplied by the storage coefficient or the specific yield (in the case of the unconfined) to determine the volume of stored groundwater. The volume of stored groundwater, present in the confined portion of the aquifer for each time period, is then calculated by multiplying the volume by the storage coefficient (S), (also called storativity) to ascertain the stored water volume. The storage coefficients are calculated by the NCDEQ and private engineering firms with data gathered from aquifer pumping tests. Mean storage coefficients of 1.6×10^{-3} and 1.81×10^{-4} are used for the confined portions of the Black Creek aquifer, respectively. For the unconfined portion of the aquifer the available storage volume is multiplied by a specific yield estimate derived from the literature, to get the volume of groundwater capable of being released from storage within each aquifer. A mean specific yield value of 0.22 is used for the unconfined portions for the aquifer (Heath and Spruill, 2004). The Black Creek aquifer in the CCPCUA contains both confined and unconfined components, as such, both mean storage coefficient and specific yield values are used in the analysis.

C.3. Results

C.3.1. Water levels

The percent changes to Black Creek water levels using the average yearly water level for the five analysis periods are summarized in Table 25. For the Black Creek wells over the time period from 1900 to 2015, the water level changes range from a loss of 0.1% to 41% (Table 26).

Date Range	Mean percent changes to Black Creek water levels
1900-2015	-15.09
1900-2002	-20.32
2002-2008	0.79
2008-2015	4.45
2002-2015	5.23

Table 29. Mean percent changes to Black Creek water levels using the average yearly water level for the five analysis periods.

	Mean % Change				
Well ID	**1900 - 2015**	**1900 - 2002**	**2002 - 2008**	**2008 -2015**	**2002 -2015**
P 21K5	-0.9	-0.9	-1.1	1.2	0.1
P 21K9	-0.9	-0.5	-1.1	0.6	-0.5
Q 27R5	-15.6	-29.8	3.6	10.7	14.2
Q 27R6	-14.8	-30.4	4.7	10.9	15.6
Q 27R7	-14	-28.2	3.9	10.3	14.2
T 29G4	-13.4	-15.5	-0.1	2.1	2.1
T 29G5	-13	-15.1	-0.1	2.2	2.1
S 22J10	-0.1	0.1	-1.3	1.1	-0.2
U 26J4	-18.9	-22.8	-1.3	5.2	3.9
V 32V6	-24.3	-26.2	1.8	0.1	1.9
R 31C1	-25.1	-25.5	0	0.4	0.4
O 30J2	-41	-41.7	0.8	-0.1	0.7
W 25F8	-19.6	-26.4	-1.9	8.6	6.8
X 24S2	-2.1	-1.1	-0.9	-0.2	-1.1
P 26U7	-22.5	-40.8	4.8	13.6	18.3

Table 30. Percent changes in water levels of individual Black Creek wells.

The mean water levels for all of the Black Creek wells illustrate an overall water loss of 15%. From 1900 until the inception of the CCPCUA in 2002 the results indicate a mean loss of 20.3%. Each subsequent period displayed water level gains of 0.79% (2002 - 2008) and 4.45% (2008 - 2015). From the inception of the CCPCUA until the end of the analysis period (2002 - 2015) the mean water levels rise was 5.23%. The Black Creek wells experience water levels declines from the pre-development conditions in 1900 until the end of the period in 2015. Despite the positive changes since the inception of the CCPCUA, these increases do not return the aquifer to pre-development water levels.

C.3.2. Storage volumes

Between 2008 and 2015, the Black Creek lost 2.16% or 804 billion gallons of groundwater between 1900 and the inception of the CCPCUA in 2002, the Black Creek (Table 27). After the CCPCUA reductions went into effect the volumetric losses abated and the water volumes began to increase.

Date Range	Volume Change
1900-2015	-1.05E+12
1900-2002	-8.04E+11
2002-2008	-2.80E+11
2008-2015	3.48E+10
2002-2015	-2.45E+11

Table 31. Change in storage volumes for the Black Creek aquifers, gallons.

The first phase of reductions, from 2002 until 2008, experienced a loss of 0.77% (280 billion gallons of water), slowing the depletion of the Black Creek. From 2008 to 2015, the depletion trend was reversed and 0.10%, or approximately 348 billion gallons of water, was added to storage in the Black Creek aquifer system. Overall, between 1900 and 2015, the Black Creek aquifer experienced a net loss of 2.82%, for a total of 1.0 trillion gallons of stored water from the system. This is a large water loss, however the CCPCUA reductions were successful in reversing the trend of aquifer depletion. The percent changes in the storage volume analyses of the Black Creek are computed and compared to the results of the water level analysis (Table 28). Figure 81 shows the percent change to the water volumes in the Black Creek aquifer during the preselected time periods.

Date Range	**Mean % Change in Water Level**	**Mean % Change in Water volume**
1900-2015	-15.09	-2.82
1900-2002	-20.32	-2.16
2002-2008	0.79	-0.77
2008-2015	4.45	0.1
2002-2015	5.23	-0.67

Table 32. Comparison of results from water level and volumetric analyses, Black Creek aquifer.

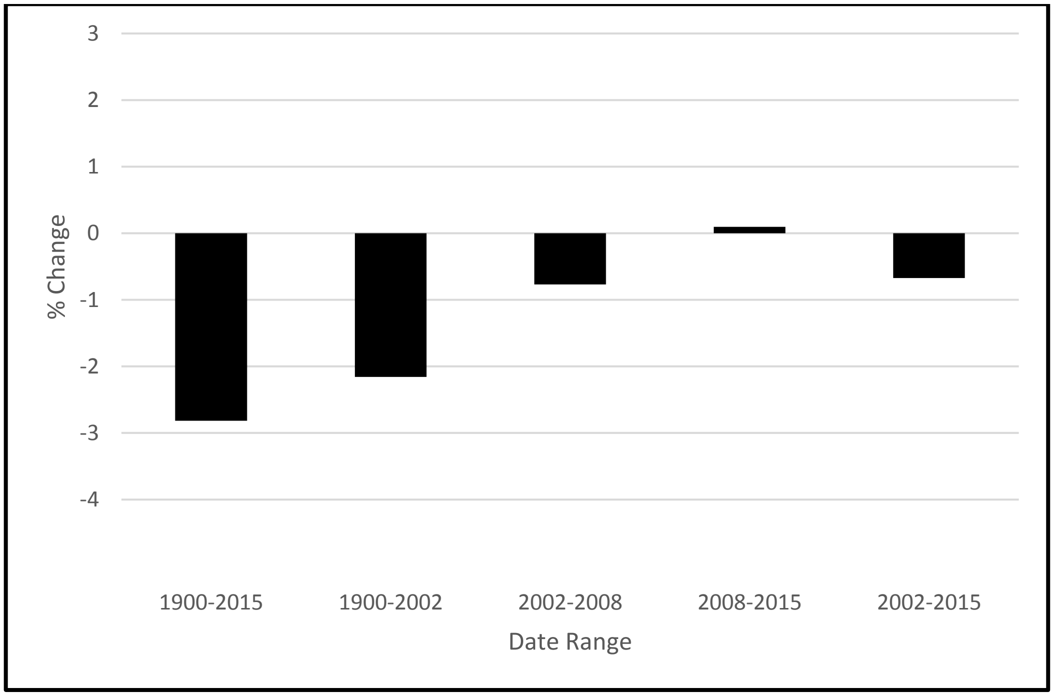

Figure 81. Percent water volume changes in the Black Creek aquifers during preselected time periods.

C.4. Limitations

There are several limitations to the analyses presented in this research. First, the early water levels were acquired from a 1912 North Carolina Geological and Economic Survey Bulletin and from recorded driller's logs (Geise et al., 1997; Clark et al., 1912). The accuracies of this well data and well locations are not comparable to that of today. Also, few monitoring wells record the aquifer conditions from the early 1900's. More complete and accurate data may be obtainable from the early 1960's. However, the hydrographs of the first two monitoring wells (in the 1960's) demonstrate that water levels had already declined from the 1900 levels (Heath and Spruill, 2003) and may not be indicative of pre-development conditions. The earliest attempt to collect thorough data was collected in 1986 and has more robust data for analysis. Yet, the first NCDEQ potentiometric maps, based on this information, illustrate an early cone of depression forming in the area of interest. Considering the apparent decline in water levels for the later and more robust data (1960's and 1986), the data from 1900 were chosen as a baseline year to reflect pre-development conditions. Bearing in mind the information for these early-time wells is limited, they are still useful to provide an approximation of the early aquifer conditions.

A second limitation includes the intermittent sampling of the water level monitoring, prior to the establishment of the CCPCUA. As a result, the frequency of sampling for water levels varies widely between the wells. This is especially true for data obtained in 2002. In addition, the wellbores are not evenly distributed throughout the CCPCUA. To address the limitations created by the paucity of data for some wells, changes to the water levels are calculated using the mean annual water level for the analysis years.

Another limitation to the analysis includes the assumption that the aquifer is homogeneous and has a uniform storativity value throughout the mapped area. Following this assumption, a mean storativity value is used to calculate storage volumes. Although this assumption is necessary due to a lack of storativity data, it makes the volume calculations somewhat suspect. These limitations will not greatly impact the storage volume calculations, as the maximum and minimum storativity for the Black Creek does not vary appreciably.

Water level data is the basis for creating potentiometric maps used to calculate the storage volumes. It could be questioned then, if the storage volume calculations are more indicative of the aquifer system than the water level data? Because water level data is limited to observation points scattered throughout the CCPCUA, the potentiometric maps used to calculate storage volumes are interpolated surfaces derived from those observation points. Using interpolation as a technique to create regularly spaced points values where no data exists (Eckstein, 1989), the interpolated point data is transformed into a facsimile and plausible representation of the true potentiometric surface (Crain, 1970). In fact, the storage volume calculations may not be more accurate than the water level data, but the interpolated surfaces may be a fuller representation of the entire CCPCUA.

C.5. Discussion

Previous analyses of the success of the CCPCUA focused on changes to potentiometric surface maps and water levels during the period 2005-2011 using data obtained from NCDEQ (e.g., Manda and Klein, 2014). The potentiometric surface maps reflect yearly water levels recorded in wells drilled in each aquifer during a chosen time period. A multi-year assessment only reveals overall changes in the size and shape of the cone of depression. The previous analyses also included time series of water levels for the Black Creek and Upper Cape Fear aquifers. Overall, the time series demonstrated positive changes in the water levels at specific locations throughout the CCPCUA. This type of analysis is limited to evaluating changes in water levels at specific locations and not necessarily the overall response within the entire aquifer system. The potentiometric surface maps and water levels reflect positive changes in the sustainability of the aquifers after the inception of the CCPCUA reductions. After the mandated reductions were enacted, the cones of depression decreased in size and the declining trends of the water levels were reversed. However, there is no quantitative assessment of the degree to which the aquifers have responded.

Earlier research showed that the differences between the lowest water levels and the water levels observed in 2012 were significant ($p< .0001$, at the 0.05 significance level) (Manda and Klein, 2014). Examples of groundwater wells with adequate records of water levels showed that median annual groundwater levels during that period rose between 3 to 56 feet (~1 to 17 meters). These observations rely on analyses of observed changes to water levels. This new research, using changes in storage, involves finding water volume changes which were controlled, in part, by the storage volume enclosed by a potentiometric surface, the base of the aquifer, the western aquifer dewatering and erosional pinchouts, the eastern limit of potable water (5,000 ppm chloride) and the ability of the aquifer to yield, store or release water. This approach quantifies changes in storage volumes within the larger aquifer system, illuminating the aquifer dynamics as a whole entity, rather than as an event at an individual well location.

The application of required pumping restrictions greatly decreased the volume of groundwater extracted from the Black Creek aquifer, which was reflected in changes in aquifer storage. These pumping restrictions resulted in a reduction in pumping from 20 million gallons per day by the Black Creek in 2002 to 10 million gallons per day in 2015 which equated to a loss of 0.67%, down from the 2.16% loss prior to the CCPCUA regulation (http://www.ncwater.org). To put these volumes in perspective, in 2015 Greenville Utilities planned to serve approximately

90,000 consumers with a daily service area demand12 million gallons of water per day (https://www.ncwater.org/Water_Supply_Planning/Local_Water_Supply_Plan/report.php?pwsid=04-74-010andyear=2015). The daily groundwater volumes saved by the CCPCUA reductions are roughly equal to the daily needs of the Greenville Utilities customers, one of the Capacity Use Area's largest service area.

The shift away from the Black Creek aquifer occurred after the construction of the Neuse River Water and Sewer (NRWASA) water treatment plant which transferred water retrieval from the Black Creek as the primary water source for the area to the use of the Neuse River. Lessening the burden on the Black Creek in areas of high withdrawals and a large cone of depression appreciably decreased the volumes of water lost in the Black Creek, as reflected in the groundwater volume calculations. Surface water provided for 6.5% of the water demands in 2002 as opposed to 19.3% in 2015.

The trend of rebounding water levels did, in fact, signal a return to a more sustainable aquifer. Yet, the percent changes in both the water level and the storage analyses show that a net loss still exists the Back Creek aquifer. Water level plots from individual Black Creek wells show positive recoveries, but are somewhat misleading, as the active monitoring well database rarely represented water levels prior to the 1970's. These plots only show a small window into the water level or potentiometric surface history of the wells. The plots display rapidly declining water levels from, at the earliest, the 1970's. They also show, in most cases, a trend reversal after the first phase reduction. Yet, most do not show recoveries back to the pre- development conditions. This is clearly displayed by the Kinston Yard, Q27R5 well (Figure 82).

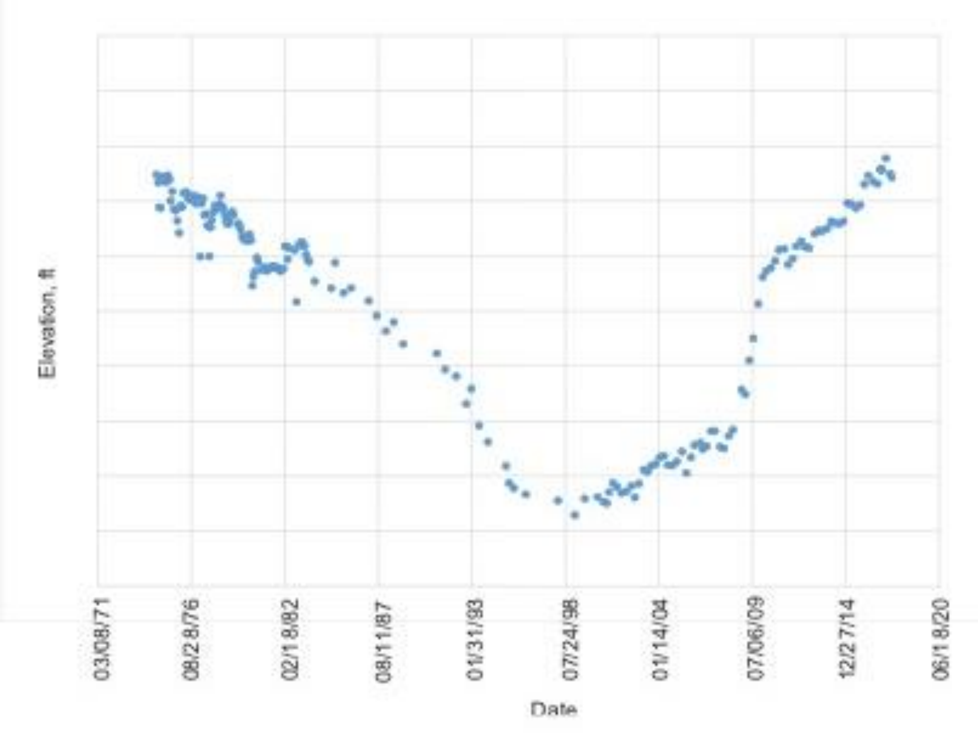

Figure 82. Typical example of a Black Creek aquifer hydrograph showing initial data dating to 1974, declining water levels to the late 1990s and rebounding water levels, especially after the end of the Phase I of the CCPCUA reductions.

Water levels have rebounded to the levels of the 1970’s, with elevations between approximately -20 and 30 feet (-6 and -9 meters), however, the original potentiometric surface was approximately 26 feet (8 meters) above sea level, more than 49 feet (15 meters) higher than current levels, implying that water levels are still recovering.

The two different methods of analyses, changes to water levels and storage volumes, consider two different regions of the aquifer system. This is evident in the losses and gains for the Black Creek aquifer (Table 27). In the short term, the water level analysis may be indicative of regions close to the wellbores and more responsive to changes in pumping. This near wellbore response may be an early reflection of the general condition of the entire aquifer storage volume.

The storage analyses may be a broader indication of the dynamics within the aquifer system than are the changes in water levels at individual locations. This system is affected by many factors, including variable available drawdown, position and thicknesses of the aquifer and the confining beds, heterogeneous hydraulic characteristics (e.g., transmissivity, storativity, hydraulic conductivity, etc.) of the aquifer and the confining beds, proximity and makeup of boundaries, proximity to other pumping wells, volumes withdrawn, and proximity to natural discharge and recharge areas. These factors interact to impact the rate of groundwater volume changes seen throughout the entire aquifer. The storage analysis suggests that the analyses maybe a delayed gage of regional aquifer conditions, whereas the water levels may indicate immediate local changes. The result of the volumetric analysis confirms a slow equalization between the reduced withdrawals and the ability of the recharge to replace the lost aquifer volumes.

C.6. Summary

The analyses of groundwater storage volumes are representative of an aquifer that is positively responding to the mandated reduced withdrawals. The analysis of the potentiometric surface provides a quantitative measure of the changes in storage volumes within the larger aquifer system, whereas the analysis of water level changes focuses on the response of the aquifer at discrete locations. The water level analyses technique, although a good estimation of positive (or negative) aquifer changes, did not consider the spatial continuity of the aquifer, whereas the alternate technique of comparing changes of storage volumes through time, does assess quantitative changes to the greater aquifer system.

Despite potential shortcomings in the analyses, both methodologies confirm the positive changes in the sustainability of the Black Creek aquifer. The storage volume analysis supplied an alternate gage and affirms the success of the CCPCUA regulation.

Although the overall changes in storage values between 1900 and 2015 are considerable, the Black Creek (-2.82%) has both respond positively to the CCPCUA reductions. The regulation achieved its goal of halting the rapidly declining water levels. Each analysis method confirms that the reductions were merited and achieved the intended goal. The results of the storage volume analyses for the Black Creek show a net loss of groundwater from pre-developmental levels, therefore it is prudent to continue the current management scheme of limiting the withdrawals in the Black Creek.

Quantifying storage volume losses and gains within the Black Creek aquifer prior to, and after thoughtful management strategies of the aquifer system are tangible indicators of the impacts of over-pumping and restricted pumping. Successful groundwater management strategies involve ongoing assessments of the aquifer system using multiple techniques. This research shows that changes in water levels only reflect relative changes in the aquifer system. Yet, with quantitative measures of the overall conditions of the aquifer obtained through storage volume analysis, groundwater managers can adapt strategies that are responsive to the changing aquifer conditions. The two different approaches presented in this research may serve as an example of both short term and long-term analysis techniques for determining the sustainability and effectiveness of management strategies on a local and regional scale.