STREAMFLOW TRENDS AND DROUGHT IN THE SOUTH ATLANTIC, U.S.: IMPLICATIONS FOR WATER MANAGEMENT AND WATER TRANSFERS

Lauren A. Patterson

A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Geography.

Chapel Hill
2012

Approved by:

Martin Doyle

Lawrence Band

Gregory Characklis

Richard Whisnant

Erika Wise

ABSTRACT

LAUREN A. PATTERSON: Streamflow trends and drought in the South Atlantic, U.S.: Implications for water management and water transfers
(Under the direction of Martin W. Doyle)

The South Atlantic has recently experienced region-wide droughts. There is concern that water scarcity may become more common or prevalent due to a warming climate. Problems associated with water scarcity are compounded by under-developed water allocation policy in the historically water abundant South Atlantic.

This dissertation examined the potential causes of water scarcity related to changes in average streamflow from 1934-2005, 1934-1969 (Mid-20th Century) and 1970-2005 (Late-20th Century). Second, the contribution of climate versus anthropogenic drivers of change in mean annual streamflow in the Late 20th Century was evaluated using Budyko curves. Third, hydrologic drought was characterized in the South Atlantic and changes in drought characteristics were assessed over multiple time periods. Fourth, water interconnections, which form an important component of water infrastructure and water management, were assessed for the potential to transfer water from a drought free to a drought stricken area.

Results showed that streamflow abruptly shifted from a drier regime in the Mid-20th Century to a wetter regime in the Late-20th Century with trends of significantly decreasing streamflow since 1970. Climate contributed to increased streamflow during the Late-20th Century throughout the South Atlantic; whereas human factors varied between basins and either amplified or decreased the climate change effect on streamflow. Human impacts were equivalent to or exceeded climate impacts in some basins. Seventy-one percent of drought events were shorter than 6 months with a recurrence interval of 6 years. Less than 7% of droughts were longer than one year, yet these longer duration droughts resulted in region-wide water scarcity. There were few significant temporal trends in drought characteristics over the studied time periods. The short interconnection distances (median=11.6 km) rarely extended beyond the spatial extent of multi-year droughts; interconnected water systems were simultaneously in drought 98±3% of the time from 2000-2008. Water managers face many challenges with a steadily growing demand and fluctuating long-term and short-term water supply needs that can be partially met through interconnections. Decision-making will benefit from monitoring changes in climate, human activities, and streamflow, as well as continually assessing the ability of current water infrastructure to perform under normal and adverse conditions.

ACKNOWLEDGEMENTS

I thank God for putting my feet in an open space, establishing the work of my hands, and blessing me with the time and resources to complete this dissertation.

I am thankful for having been given the privilege to work with such a supportive and top-notch committee. I thank Martin Doyle for pursuing me to come to graduate school, as well as for his encouragement, teaching me to think critically, freedom to explore my own interests, and his wise counsel. He has taught me something about what it means to have a vision and how to work toward accomplishing those goals. His method of mentoring as a “crushing hammer, guiding light” has kept me humble and made me a better researcher. I am thankful for Larry Band’s guidance, his ability to make connections between diverse concepts, and his brilliant solutions to address seemingly impossible problems. I am greatly appreciative of Greg Characklis’ clear insight, advice, and enthusiasm. His water resources economics class was especially instrumental in teaching me about scarcity and the complex politics and economics of water. I am thankful for Richard Whisnant’s involvement in water policy, for teaching me the importance of stories as a means to communicate, and for showing me how research and policy can mix. I appreciate Erika Wise’s willingness to take me on in her first year at Carolina, for encouraging me to learn atmospheric processes, for providing feedback, and for brainstorming ideas.

I am deeply grateful to Brian Lutz for his willingness to work with me, savvy statistical knowledge, amazing Rcran programming skills, and editing prowess. His willingness to invest time and energy to improve this dissertation has been incredibly encouraging and confidence boosting. I am also thankful for the friendship and assistance of my office mate, Anne Trainor. She was always one step ahead in her research and always willing to teach me the useful methods and skills she learned. I owe her a deep debt of gratitude for convincing me that programming in SAS and R was more time efficient than excel and well worth learning.

Thank you Doyle lab members, past and present. Daisy Small, Jen Costanza, Jon Duncan, Jeff Muehlbauer, Autumn Thoyre, and company have a diversity in expertise and personality that kept graduate school interesting and enjoyable. I am also thankful for the support of UNC's Geography Department, particularly Barbara Taylor Davis, Nell Phillips, and Daniel Warfield.

My time working at the Environmental Finance Center at UNC was a blessing. Jeff Hughes, Shadi Eskaf, Mary Tiger, Glenn Barnes, and others were a wonderful team to work with and have taught me a lot about working with local governments, and of course, water-related financing. I am especially grateful to Shadi for being patient and willing to teach me about interconnections, dashboards, and how to think through problems by drawing them out on paper.

I am deeply honored and thankful to the institutions that chose to fund my research, including the Udall Foundation, Periship Program, and National Science Foundation. It is my hope that these institutions are pleased with the product of their investment.

I can never adequately express my depth of gratitude for the support and love given to me by my family and friends. Jessie Stewart and Brooke Wheeler have been amazing roommates and constant companions – thank you for letting me into your homes. Gretchen Logterman, Sarah Hancock, Emily Mathers, Dana Saleeby, Nicki Jarret, Heather Deans, and Charlie Shaefer have been a light to my feet and incredibly patient in teaching me what it means to live. The Peter's, Hawke's, Perry's, Stepp's, Gervais' and many others have let me into their lives and taught me what it means to be part of a family and to love and serve others. Thank you for investing in me and for changing a life. I pray that someday, or perhaps every day, I may return the gift by helping to bring living water to others.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 5

CHAPTER 6

CHAPTER 1

INTRODUCTION TO WATER RESOURCES IN THE SOUTH ATLANTIC

1876 – "The 100 meridian is the divide between the dry west and the lush east" – John Powell

1.1 Introduction to Water Scarcity

The South Atlantic, a three state area referring to North Carolina, South Carolina, and Virginia, has historically experienced abundant water availability to meet demand and has made it unnecessary to develop region-wide water allocation regulations. Currently, institutional water policies and regulations for allocating water remain under-developed in the South Atlantic. Two recent region-wide, multi-year droughts (1998-2002 and 2006-2008) brought reservoirs to record-lows and placed unprecedented stress on water systems to meet customer demand. The back-to-back experience of water scarcity (i.e. insufficient supply to meet demand) has catalyzed a transition in water resources management to be more proactive in addressing water allocation issues in the South Atlantic.

While drought (a deficit in water from what is normally available) triggered water scarcity, the impacts of the drought were exacerbated by the growth in population (increased water demand), changes in land use (impacts water demand and evaporation rates), and non-conservative water use practices (Seager et al., 2009). Jim Thebaut's upcoming documentary "Running Dry-Beyond the Brink" states that both drought and water scarcity are of increasing concern for the American Southwest, Texas, and the Southeast. This concern was again brought into the spotlight, when on January 30, 2012 Spicewood, TX, a community of 1,100 ran out of water during the driest conditions in recorded history after a year of severe drought conditions (Weissert and Plushnick-Masti, 2012). This is the first time a community has run out of water in Texas, and Spicewood is now paying thousands of dollars to transport water in tankers from a utility 17 miles away.

Previously, during the 2006-2008 drought, the City of Raleigh, NC (population over 400,000) nearly emptied Falls Lake, the only water supply for the city. Larger cities, such as Atlanta, GA (population over 5 million) were also within months of running out of water as Lake Lanier reached record lows. The risk of running out of water has driven these cities to search for ways to increase their water supply portfolio and reduce water demand. Solving water scarcity in an ad-hoc fashion during emergencies for individual cities has historically worked, but may not be efficient or work as well in the future as the margin between demand and supply decreases and decisions made by individual consumers will have larger impacts on other consumers connected to the same water source.

1.2 Policy Legacies to Address Water Scarcity

Since "today's policy choices become tomorrow's policy constraints" (Crase 2007), it is essential to develop an understanding of the water-related policy and institutions currently in place, how they came to be in place, and how they constrain future policy choices related to water scarcity. There is no national water policy for water allocation. This is likely a result of diverse hydrologic conditions throughout the country (Crase, 2007) and the focus on state-based federalism (Gerlak 2005). Federal water policy has been limited to navigation (e.g. River and Harbor Acts 1899), flood control (e.g. 1936 Flood Control Act), and more recently water quality (e.g. 1972 Clean Water Act) as the social attitude towards water expanded from development to include environmental restoration (Feldman, 2009; MacDonnell, 2009; Gerlak, 2005). The climatologic, hydrologic, and socio-economic diversity of the nation makes it unreasonable to have a one-size fits all policy regarding water allocation. As a result, states have inherited the responsibility for developing policies to manage water resource allocation as needed.

The British water policy of Riparianism was imported with the 13 colonies East of the Mississippi River (MacDonnell, 2009; Musgrave, 2007). The riparian doctrine couples water rights to land property rights immediately adjacent to a surface water body. All adjacent owners have equal rights to the ‘reasonable’ use of water. Reasonable use is a vague term, and unless adjudicated, riparian rights are not quantified. Riparianism was initially successful because there was enough water to meet demand. Since there are not defined rules to allocate water, shortages are to be equally shared by all water users regardless of how water is being used (e.g. municipal verses agricultural).

Pure Riparianism is inadequate for dealing with water scarcity (Dellapenna 2002) and leaves states and local jurisdictions to develop their own policies and legislation. As the South Atlantic region moves toward reforming water policy to address scarcity, each state is moving towards reforming their individual legislation and policies that move away from true Riparianism and toward “Regulated Riparianism” (Lopsteich, 2010; Dellapenna, 2002). Yet, each state is inextricably linked to adjacent states through shared watersheds, which are being fragmented by inconsistent water policies that inhibit regional collaboration to manage water resources. This has resulted in some conflict, particularly between upstream and downstream states for water rights (e.g. the Apalachicola-Chattahoochee-Flint case between Alabama, Florida and Georgia, and the case between North and South Carolina for the Catawba River Basin). A fundamental problem in addressing these cases is that there are no uniform, legal water rights or rules to allocate water.

The two fuels igniting conflict in the “water rich East” are intense population growth and unclear rules as to who is entitled to water (Barnett, 2007). All three states included in this study area have enacted water policies over the past decade that have begun to address water scarcity.

These policies include promoting water conservation, developing minimum release protocols during the federal relicensing of reservoirs, requiring water permits for large withdrawals, and inter-basin transfer regulations; and these changes in policy have signaled a shift towards Regulated Riparianism with more regulations on water resource allocation.

Water policy reform is occurring in the South Atlantic. It will either change as a result of proactive, intentional leadership or reactionary, ad-hoc crises. Undoubtedly, a proactive approach would be ideal because policies would be intentionally designed to be compatible with other policy goals. For that to happen, an understanding of hydrological, geographical, historical, social, economic and political perspectives are required (Crase, 2007).

1.3 Water Scarcity Drivers in the South Atlantic

This dissertation seeks to contribute one piece to the picture by informing water policy regarding how water resource availability has been changing in the South Atlantic. There is considerable interest in answering this question because many scientists believe that warming temperatures are intensifying the water cycle (e.g. Huntington, 2006). An intensified water cycle would translate into more frequent and severe floods and droughts because of the increased ability for the atmosphere to hold more water (Trenberth, 2011). The theory is based on the Clausius-Clayperon relationship that describes the water-holding capacity of the atmosphere as a function of temperature (~7% change in the volume of water for 1^{o}C in temperature). This relationship is less evident in the South Atlantic because evaporation is energy limited, rather than water limited (Huntington, 2006). Since more water is held in the atmosphere prior to being released, the intensity of precipitation events will increase and become less frequent (Trenberth, 1999). Thus, the amount of precipitation may not change but the distribution of precipitation events may change in such a way as to have more frequent extremes of both flood and drought. However, changes in global variables may not be reflected in regional or local changes due to feedbacks in atmospheric processes, land cover, and water management (Diffenbaugh et al., 2005). Thus, it is important to study climatic changes at regional scales.

Changes in climate (precipitation or temperature) translate to changes in streamflow (Q=P-E; where Q is streamflow, P is precipitation, and E is evaporation which is impacted by temperature). Streamflow is also impacted by human-induced changes such as reservoir storage, land cover, and water demand (Arrigoni et al., 2010). For example, reservoirs are often managed to reduce streamflow variability by holding more water during recharge months (decreasing streamflow) and releasing more water during summer months (increasing streamflow). Growing populations require more water, which reduces streamflow, and water demand also fluctuates during a year with peak demand during summer months. Human factors can vary widely between basins located a few kilometers apart; thereby, requiring study at the scale or basin of interest. Thus, climate and human factors can change the amount of water in streams and those changes can vary between basins and regions.

Management efforts can benefit from studies that explicitly examine changes in the water cycle and the regional capacity for water systems to adapt to changes in the average condition. This information can also be tied with how current water management policies and infrastructure alleviate or exacerbate changes in streamflow, particularly during extreme conditions such as drought. Monitoring key elements of the water cycle (i.e. precipitation, streamflow, and temperature) provides “irreplaceable information that is particularly critical in a non-stationary environment” (NRC, 2011). This study attempts to answer some of these questions in the four chapters outlined below by exploring streamflow trends in watersheds that are subject to a broad range of anthropogenic influences.

1.4 Dissertation Outline

The over-arching goal of this dissertation is to understand how average and drought streamflow conditions have changed in the South Atlantic. I also sought to understand how much of the change in streamflow can be attributed to climate and human factors. Lastly, I examined the capacity of water transfers in North Carolina as a means to mitigate drought by redistributing water supply (Figure 1.1).

Chapter 2 examines trends in average monthly streamflow for 54 stream gauges over different periods of time (1934-2005; 1934-1969; 1970-2005) to determine if surface water supply is changing. Trend analysis of how these elements have changed over time provides one line of evidence to assess whether there has been a significant change in the water cycle. Estimates of mean climate are more credible than estimates of climate variability and trends are generally more credible over larger spatial areas and longer temporal averaging periods (i.e. monthly or annually; Brown et al., 2011). A change in surface water availability will have significant implications for how water is managed because that will alter the relationship between supply and demand (Figure 1.2).

Chapter 3 examines how much of the change in mean annual streamflow between two time periods (1934-1969 and 1970-2005) is due to climate or direct human modification. Direct human modification includes factors such as reservoir storage, land cover change (urbanization, agriculture, forestry), and water demand. This method utilizes Budyko curves, which represents the interdependence between mean annual evaporation and potential evaporation for precipitation in a river basin. The Budyko curve in the first period (1934-1969) establishes "normal" climate and watershed characteristics for the basin. The change in the Budyko curve in the second period (1970-2005) can then be separated into climate (moves along the Budyko curve) and human (movement off the Budyko curve) contributions (Wang and Hejazi, 2011). Understanding the relative contribution of climate and direct human impacts to changes in mean annual streamflow would be a significant asset to inform water resource management policies and infrastructure decisions.

Chapter 4 characterizes hydrological drought (frequency, duration, deficit, severity, and spatial extent) in the South Atlantic and explores whether these characteristics have changed over the same time periods examined in Chapter 2. Drought has been the catalyst for much of the policy reformation observed in the South Atlantic over the last 15 years, yet few (if any) analytical studies of drought are available specifically for this region.

Chapter 5 develops a method to explore the utility of water transfers between water systems to alleviate drought conditions. This method assesses the probability of a system buying water being in-drought at the same time as the system selling water. The results from this analysis provide information regarding which connected systems had the lowest probability of simultaneously being in drought conditions, and whether the difference between near buy systems was significantly different and would benefit from a future interconnection from a drought only perspective. In addition, this chapter looks at the capacity for current interconnections to alleviate long-term water supply and demand imbalances.

The combination of these analyses will provide a picture for the average streamflow water supply in the South Atlantic, how these supplies are changing over time, what is driving these changes, and how extremely dry periods impact water supply. This dissertation will also highlight the role and capacity for interconnections as a short-term emergency, and long-term regular, solution to alleviate water scarcity.

1.5 Figures

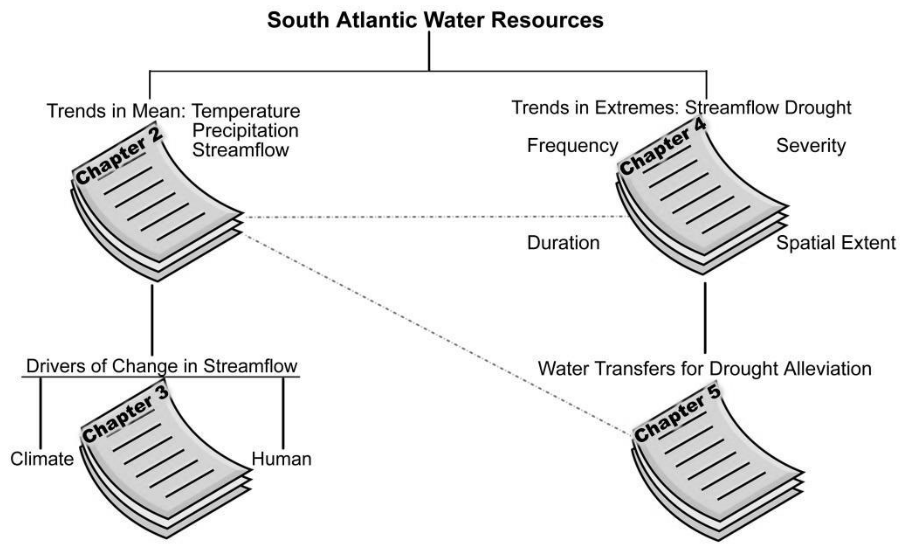


Figure 1.1: Schematic outlining dissertation chapters and their relationship to one another. Solid line is a direct connection between chapters. Dashed line is an indirect connection.

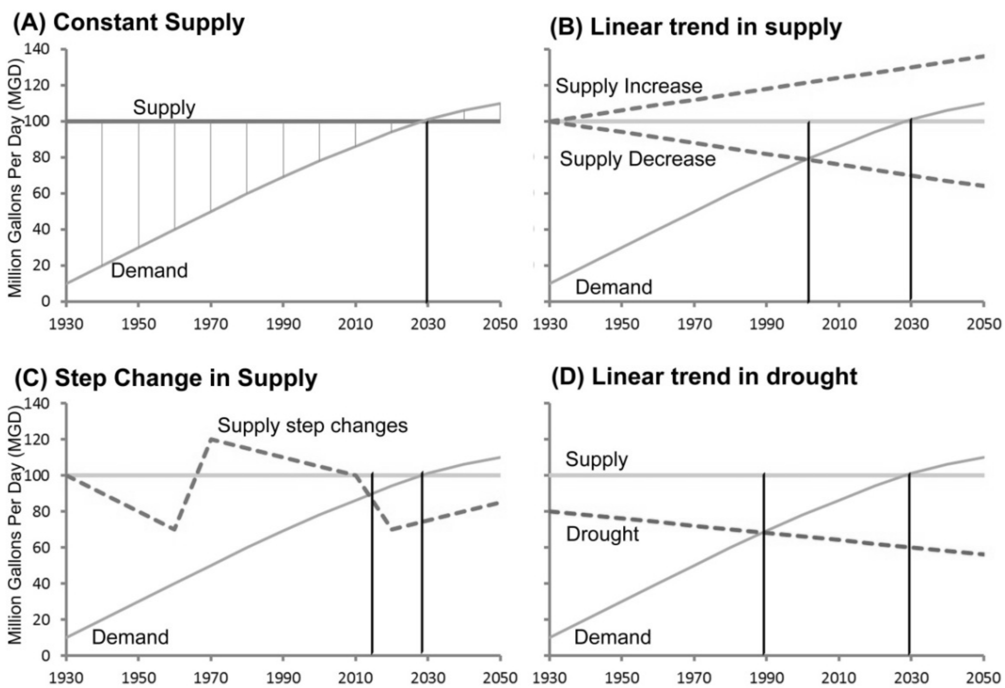


Figure 1.2: Impact of changes in streamflow and drought on water scarcity. (A) No trend in streamflow. Constant supply and rising demand are equal in 2030. (B) Linear decrease (increase) in streamflow result in supply and demand intersecting earlier (later) than 2030. (C) Step change in streamflow with linear trends in-between increase the difficulty in predicting water scarcity. (D) Changes in drought conditions can result in short periods of scarcity.

1.6 Literature Cited

Andreadis, K.M. and D.P. Lettenmaier. 2006. Trends in 20th Century Drought over the continental United States. *Geophysical Research Letters* 33, L10403, doi. 10.1029/2006GL025711.

Arrigoni, A.S., M.C. Greenwood, and J.N. Moore. 2010. Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of river in the Northern Rocky Mountains, United States. *Water Resources Research* 46 (W12542), doi:10.1029/2010WR009162.

Barnett, C. 2007. Mirage: Florida and the Vanishing Water of the Eastern U.S. University of Michigan Press, Detroit, MI, pp 240

Brown, C., W. Werick, W. Leger, and D. Fay. 2011. A decision-analytic approach to managing climate risks: application to the upper Great Lakes. *Journal of American Water Resources Association* 47 (3): 524-534, doi: 10.1111/j.1752-1688.2011.00552.x

Crase, L. 2007. Lessons from Australian Water Reform. *In:* Crase, L. (ed.) *Water Policy in Australia: The Impact of Change and Uncertainty*. Resources for the Future, Washington D.C., pp. 248-266.

Dellapenna, J.W. 2002. The law of water allocation in the Southeastern states at the opening of the twenty-first century. *UALR Law Review* 25: 9-88.

Diffenbaugh, N.S., J.S. Pal, R.J. Trapp, and F. Giorgi. 2005. Fine-scale processes regulate the response of extreme events to global climate change. *PNAS* 102 (44): 15774015778, doi: 10.1073/pnas.0506042102

Feldman, D.L. 2009. Preventing the repetition: Or, what Los Angeles' experience in water management can teach Atlanta about urban water disputes. *Water Resources Research* 45, W04422, doi: 10.1029/2008WR007605.

Gerlak, A.K. 2005. Federalism and U.S. Water Policy: Lessons from the Twenty-First Century. *Journal of Federalism* 36 (2): 231-257.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* 319: 83-95, doi: 10.1016/j.jhydrol.2005.07.003.

Lopsteich, R.A. In Press. Water Allocation: The Florida Story-Past, Present and Future

MacDonnell, L.J., 2009. Return to the River: Environmental Flow Policy in the United States and Canada. *Journal of the American Water Resources Association* 45(5):1087-1099. DOI: 10.1111⁄ j.1752-1688.2009.00361.x

Musgrave, W. 2007. Historical Development of Water Resources in Australia: Irrigation Policy in the Murray-Darling Basin. *In:* Crase, L. (ed.) *Water Policy in Australia: The Impact of Change and Uncertainty*. Resources for the Future, Washington D.C., pp. 28-43

NRC (National Research Council). 2011. Global change and extreme hydrology: testing conventional wisdom. Report by the Committee on Hydrologic Science Water Science and Technology Board. *National Academies Press*, Washington, D.C. ISBN 978-0-309-21768-2, pp. 45

Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change. *Journal of Climate* 22, pp. 5021-5045, doi: 10.1175/2009JCLI2683.1.

Trenberth, K.E. 2011. Changes in precipitation with climate change. *Climate Research* 47: 123-138, doi: 10.3354/cr00953.

Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* 42: 327-339.

Thebaut, J. Forthcoming. Running Dry: Beyond the Brink. *Last accessed February, 2012*. http://awramedia.org/mainblog/2011/12/07/preview-jim-thebauts-running-dry-beyond-the-brink/

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47 (W00J12), doi: 10.1029/2010WR010283.

Weissert, W. and Plushnick-Masti, R. 2012. Texas town relying on tanker trucks for water. *The Kansas City Star*. Published January 30, 2012. *Last accessed February, 2012.* http://www.kansascity.com/2012/01/30/3400062/water-trucked-to-texas-town-where.html#storylink=misearch

CHAPTER 2

STREAMFLOW CHANGES IN THE SOUTH ATLANTIC, US DURING THE MID AND LATE 20TH CENTURY[1]

2.1 Abstract

Repeated severe droughts over the last decade in the South Atlantic have raised concern that streamflow may be systematically decreasing, possibly due to climate variability. We examined the monthly and annual trends of streamflow and climate (precipitation and temperature) in the South Atlantic for the time periods: 1934-2005, 1934-1969, and 1970-2005. Streamflow and climate trends transitioned ca. 1970. From 1934-1969, streamflow and precipitation both increased and decreased within similar regions; while temperature decreased throughout the region. From 1970-2005, streamflow decreased, precipitation decreased, and temperature increased throughout the South Atlantic. It is unclear whether these will be continuing trends or simply part of a long-term climatic oscillation. Whether these streamflow trends have been driven by climatic or anthropogenic changes, water managers face challenging prospects of adapting to decadal-scale persistently wet and dry hydrologic conditions.

[1] Chapter 2 was co-authored with B. Lutz and M.W. Doyle and submitted to JAWRA

2.2 Introduction

Water management policy and infrastructure throughout much of the Atlantic drainage basin within Virginia (VA), North Carolina (NC), and South Carolina (SC; hereafter the 'South Atlantic') was developed and implemented under assumptions of climate stationarity, an assumption that is increasingly questioned (Milly et al., 2008). Knowing past, present, and predicted future temporal and spatial trends in water availability is essential to understand the possible implications of climate variation on water availability and to develop policies and institutions that can effectively manage water resources in the South Atlantic.

Streamflow is responsive to both changes in climate and anthropogenic activity, making them a priority for study. Several recent studies have explored streamflow trends at the national scale (e.g., Andreadis and Lettemaier, 2006; Lins and Slack, 2005; McCabe and Wolock, 2002; Lettenmaier et al., 1994). The general conclusion of these studies was that streamflow has increased in the United States, particularly since the 1970's. Yet throughout much of the South Atlantic repeated periods of water scarcity have been experienced over the last decade. Previous national scale findings do not align well with regional perceptions or observations. Focusing or relying solely on national trends may over-shadow the presence of regional scale trends (Zhu and Day, 2005), yet to our knowledge no previous studies have explicitly explored streamflow trends in the South Atlantic.

Many of the national scale studies that have found increasing streamflow trends also found increasing precipitation trends, indicating a climatic driver to streamflow change (Andreadis and Lettenmaier, 2006; Lettenmaier et al., 1994; Lins and Slack, 2005). Climate influences the amount of water available at all spatial scales ranging from local (10^1 km^2) to regional (10^5 km^2) to global (10^8 km^2). At the regional and global scale, climate is often the major determinant of streamflow quantity and timing (Arrigoni et al., 2010; Frederick and Gleick, 1999). At more local spatial scales human influences, such as reservoirs and diversions, become increasingly important (Claessens et al., 2006).

The South Atlantic has also experienced large population growth in recent decades (Wachob et al., 2009; Blowe et al., 2006), resulting in land use change, which has in turn impacted the timing and quantity of streamflow (Sun et al., 2005; Smith et al., 2002). There have also been changes in water use and hydro-electric power generation (Wachob et al., 2009). As a result, disentangling the potential effects of changing climate versus anthropogenic changes on streamflow is challenging.

Regardless of causes, a necessary first step is determining whether climate and streamflow exhibit spatially and temporally consistent trends (Douglas et al., 2000). In this article, we examine trends in streamflow throughout the South Atlantic using data from long-term gauging stations. We assess if trends are consistent across different time periods, as well as spatially within the study area. We also assess changes in temperature and precipitation to determine if they are spatially and temporally consistent with observed changes in streamflow. Consistency between climatic and hydrologic trends would suggest climate change is an important driver of streamflow trends, but would not distinguish between, or quantify, the relative importance of changing climate verses anthropogenic impacts.

2.3 The South Atlantic Region

We examined trends in climate and surface streamflow volumes in the Atlantic draining portions of the South Atlantic states (Figure 2.1). Three basins start in VA and drain in an easterly direction, while four basins begin in NC and drain in a south-easterly direction. Of these seven river basins, Cape Fear is the smallest (~25,370 km^2) and the Santee-ACE is the largest (~61,100 km^2).

The South Atlantic is comprised of three physiographic provinces: the Mountain Region, Piedmont, and Coastal Plain, which differ in underlying geology, topography, climate (National Climatic Data Center: http://climod.meas.ncsu.edu/), and land cover (National Land Cover Data: http://seamless.usgs.gov/nlcd.php). The high elevation Mountain Region is predominantly forested with highly variable precipitation volumes resulting from orographic effects. The Piedmont has a rolling topography with a mosaicked landscape of forest, agriculture, and urban development. The Coastal Plain is relatively flat and land use is dominated by agriculture. Mean annual temperature increases from the mountains (11^{o}C) to the ocean (16^{o}C), and mean annual precipitation is typically lower in the Coastal Plain (average of 115 cm) than inland (up to 200+ cm).

2.4 Data and Methods

We analyzed climate and streamflow data from 1930 to 2010. This time period allowed us to maximize our sample size while avoiding analyzing records of variable length (longer records were truncated to 1930). The time period of analysis is significant because even non-parametric trend analyses are sensitive to the choice of time period (McCabe and Wolock, 2002), particularly to edge effects if the beginning or end of the record coincides with an abnormally wet or dry period (Hayhoe et al., 2007). Widespread drought occurred in the South Atlantic in the early 1930's and late 2000's (Figure 2.2). As a result, we truncated our analysis to range from 1934 to 2005 since these years represent periods of transition between wet and dry conditions, and would decrease the likelihood of biasing the trend analysis. The change in start and end points did not significantly change our results from using the full record (1930-2010).

Previous studies found an abrupt shift in climate and streamflow around 1970 (Baines and Folland, 2007; McCabe and Wolock, 2002). Preliminary analysis of our data showed a similar shift. Thus, in addition to analyzing the entire record, we also analyzed data separated into the "Mid-20th Century" (1930-1969) and the "Late-20th Century" (1970-2005) in order to observe general streamflow trends while accounting for the abrupt shift.

Monthly average streamflow data were acquired from the United States Geologic Survey (USGS) stream gauge network (http://nwis.waterdata.usgs.gov/nwis). Gauges having records from 1930 to 2010 with less than 10% missing data (n=54) were included in the analysis. Over half of the stream gauges (n=26) were part of the Hydro-Climatic Data Network (HCDN), a national dataset of

USGS gauged streams determined to be free of anthropogenic influences, such as dams, diversions, and significant land use change during the period of record (up until 1988; Lins and Slack, 2005). Changes in streamflow at HCDN sites can be attributed predominantly to changes in climate (Hodgkins et al., 2007). All streamflow data were normalized by drainage area and converted to centimeters (cm).

Monthly total precipitation and mean temperature data were obtained from the U.S. Historical Climatology Network (HCN) dataset that was developed by the National Climatic Data Center and hosted through the Southeast Regional Climate Center (http://climod.meas.ncsu.edu/). HCN data are adjusted for biases that develop due to changes in station location and instrumentation (Hodgkins et al., 2007). We only used precipitation (n=90) and temperature (n=60) data from stations having continuous records from 1930 to 2010 and less than 10% missing data.

2.4.1 Trend Analyses:

Our primary goal was to analyze long-term trends in streamflow and climate. Seasonal Mann Kendall (SMK) tests provide information regarding the direction and significance of trends. Several advantages of non-parametric test statistics are that they allowed the data to: (1) be non-normal (Andreadis and Lettenmaier, 2006), (2) have missing values (Hirsch and Slack, 1984), and (3) have correlations between seasons (Campbell et al., 2011; Zhu and Day, 2005). Corrections for seasonal correlations were made by inflating the variance of the test statistic (Hirsch and Slack, 1984). The SMK tests for monotonic trends while accounting for seasonality by calculating the trend for each month and combining the results to determine whether the aggregated monthly trends were significant (Hirsch and Slack, 1984). The SMK would not be significant if increases in some months were balanced by decreases in others. As a result, we also report all monthly Mann Kendall (MK) results. We calculated trend slopes using non-parametric Kendall-Theil Robust Line, a statistic which calculates the slope of the trend line as the median of all possible pairwise slopes between two continuous variables (e.g. streamflow and time; Hodgkins et al., 2007; Claessens et al., 2006; Granato, 2006). The slope was multiplied by the length of time to get an estimated total change during each period.

2.4.2 Cluster Analysis

We were also interested in the spatial trend of streamflow changes. We examined the spatial association for climate and streamflow trends at each time period using Anselin Global and Local Moran's I statistic (Anselin, 1995). Global Moran's I provided one statistic to indicate whether trends are homogenous, dispersed, or clustered throughout the South Atlantic. Local Moran's I gave a statistic for every station to indicate the presence or absence of significant spatial correlation with nearby stations relative to all stations within the South Atlantic. This provided a quantitative metric of determining if stations had positive or negative spatial autocorrelation. High positive Z scores indicate that the surrounding stations have positive spatial correlation and the test distinguishes between clusters of high (low) values (i.e. stations with increasing (decreasing) trends). Stations with low z-scores that have high values near low values or vise-versa have a negative correlation.

2.5 Results

2.5.1 Annual Streamflow Trends

Few stations exhibited significant streamflow trends over the entire record (1934-2005). Two sites showed a significant increase in streamflow while seven showed declines (Table 2.1). While few trends were significant, the directionality of observed changes in streamflow was consistent within basins (Figure 2.3A). For example, the Roanoke, Neuse-Pamlico, and Santee-ACE river basins had predominantly decreasing streamflow, while the Yadkin-Pee Dee and Potomac-Shenandoah river basins had predominantly increasing streamflow.

In contrast, approximately 50% of all stations exhibited significant trends over the shorter time periods, with nearly all trends being negative (Table 2.1). The magnitude of decline in the Mid-20th Century (1934-1969; HCDN = -0.99±0.48; non-HCDN = -0.80±0.40) was similar to the magnitude of decline in the Late-20th Century (1970-2005; HCDN = -0.96±0.49; non-HCDN = -1.32±0.76).

During the Mid-20th Century, significant decreases in streamflow occurred in VA river basins and the headwaters of the Neuse-Tar Pamlico and Cape Fear river basins, while significant increases occurred in downstream sections of the Yadkin-Pee Dee and Santee-ACE river basins (Figure 2.3B). In contrast, during the Late-20th Century, nearly all gauges in all river basins showed declining streamflow (Global Moran's p-value < 0.0001), with larger declines in streamflow clustered throughout the Piedmont Province of SC and along the Mountain/Piedmont transition in NC (Figure 2.3C). Anselin's Local Moran I showed the presence of positive spatial autocorrelation between stations during the Mid- and Late-20th Century periods. The location of increasing and decreasing clusters reversed between the two sub-periods (figure not shown).

HCDN streams were not more likely to exhibit a significant trend in streamflow than non-HCDN sites and the magnitude of change was comparable between the two (Table 2.1). Since differences between HCDN and non-HCDN sites were not significant, we do not distinguish between them any further.

2.5.2 Monthly Streamflow Trends

Streamflow in the South Atlantic peaks in March and is lowest in September (Figure 2.4A). For the entire record, there were few significant monthly trends and most of those trends occurred as declining streamflow in summer months (July and August, Figure 2.4B). Figure 2.4 displays the range of changes in streamflow with the number of significantly increasing (decreasing) sites located above (below) the box plot for each month.

During the Mid-20th Century, a few sites (n=3) showed large increases in March streamflow, but nearly half of the sites showed small, significant declines during late summer months (July-September; Figure 2.4C). These widespread declines during summer months drive the negative trends in annual streamflow. In contrast, during the Late-20th Century, no sites showed a significant positive trend in any month and significant declines, while not as frequent, occurred most commonly during early summer (May; Figure 2.4D).

2.5.3 Climate Trends: Temperature

Over the entire record, 36 of the 60 climate stations showed a significant decline in mean annual temperature of approximately 1.0°C (Table 2.2). Seven stations exhibited a significant positive trend, and these were smaller in magnitude (+0.52°C) than the declines observed at stations with negative trends. During the Mid-20th Century, there was a significant decrease in temperature at 80% of stations (n=49; average decline of -1.3°C), with no positive trends at any station (Table 2.2). In contrast, during the Late-20th Century we found significant increases (average 0.72 °C) in 27 (45%) of the stations, while nine stations showed significant cooling (average -0.76°C). Eight of these nine stations showed significant cooling throughout the period of record.

Spatial trends in temperature showed fairly uniform cooling (1934-2005 and 1934-1969) or warming (1970-2005) throughout the region (Figure 2.4). The Global Moran's I was not significant for any of the time periods, indicating temperature change was fairly homogenous throughout the South Atlantic.

Temperature changes during the winter and summer months were responsible for the majority of significant temperature trends observed in the annual data (Figure 2.6B). During the Mid-20th Century, many sites showed dramatic cooling in early winter (January temperatures declined by -3.2±0.8°C) and a more modest cooling that was distributed over summer months and into autumn (June-October by -1.9±0.7°C; Figure 2.6C). Conversely, during the Late-20th Century warming trends were driven by increases in mid-winter (February = 1.9±0.9^{o}C) and mid –summer (June and July = 1.4±0.4^{o}C) temperatures at significant sites (Figure 2.6D).

2.5.4 Climate Trends: Precipitation

There were few significant trends in precipitation during all time periods with less than 10% of available stations showing significant change (Table 2.3). Both the Mid- and Late-20th Century had a similar number of stations increasing (n=6) and decreasing (n=5) in precipitation. The Late-20th Century exhibited only decreasing trends in precipitation. Where significant trends were found, regardless of trend direction, the average change was less than 2% of the average annual precipitation.

Although the number and magnitude of trends in precipitation were small, there was significant spatial clustering (Figure 2.7). During the Mid-20th Century, precipitation increases were predominantly located in the Mountain/Piedmont Provinces of NC and in SC, while VA and the headwaters of the Cape Fear and Neuse/Pamlico river basins decreased (Figure 2.7). In contrast, during the Late-20th Century, precipitation declines were located in the Mountain and Piedmont Provinces of North and South Carolina. Precipitation changes were regionally clustered during the Mid-20th Century (p-val = 0.001). Significant local clusters of positively correlated precipitation change occurred in both the Mid- and Late-20th Century (figure not shown).

Precipitation in the South Atlantic showed high variability and little seasonality with a small increase in rainfall occurring from June to September (Figure 2.8A). For the entire record, 18 of the 90 climate stations experienced a significant decrease in July precipitation (average = -5.6±2.9 cm), while 19 stations experienced a significant increase in October precipitation (average= 4.3±2.5cm; Figure 2.8B). During the Mid-20th Century, 15 of the 90 stations had a significant decrease in precipitation for the month of July (average = -8.8±2.2cm; Figure 2.8C). Many stations in the Late-20th Century showed significant negative trends at the beginning (May = -7.7±2.5cm) and end

(October = -6.9±1.3cm) of the growing season (Figure 2.8D). While annual trends in precipitation were small (<2% of annual total precipitation), monthly declines in precipitation had a larger impact as it accounted for up to 47% of that months average precipitation. Overall, however, the monthly data were noisy and limited our ability to resolve significant trends in the annual data.

2.6 Discussion

There were few significant trends in streamflow over the entire 71-year record (1934-2005). However, there was an abrupt shift in climate and hydrology (an increase in streamflow) that occurred around 1970 that overwhelms our ability to assess trends at this timescale. Before (Mid-20^{th} Century; 1934-1969) and after (Late-20^{th} Century; 1970-2005) this transition we observed many significant trends in both streamflow and climate (Table 2.1 to Table 2.3). The largest declines in streamflow were observed during the Late-20^{th} Century. Declines in streamflow were broadly distributed throughout the South Atlantic in recent decades, with the most significant decreases occurring in the western Piedmont of North Carolina and throughout South Carolina (Figure 2.3C). During this period, annual temperatures throughout the region have increased significantly by nearly 1^{o}C (Table 2.2 and Figure 2.5C), with winter months approaching a 2^{o}C increase in temperature (Figure 2.6D). An increase of this magnitude has the potential to significantly alter evapotranspiration rates and disrupt infrastructure and agriculture (Band and Salvesan, 2009) particularly since many sites showed significant warming during drier summer months (Figure 2.6D). Evapotranspiration accounts for a significant amount of the total water flux through ecosystems, particularly in the heavily forested Mountain and Piedmont provinces (Sun et al., 2005).

Although precipitation is highly variable and trends were difficult to detect, significant declines during the Late-20^{th} Century were observed throughout the Mountain/Piedmont provinces of North and South Carolina (Figure 2.7C) where the largest declines in streamflow were observed (Figure 2.3C). The greatest decrease in precipitation and streamflow both occurred in May (Figure 2.8D and

Figure 2.4D, respectively), during the growing season. There were also decreases in streamflow during winter months when peak groundwater and reservoir recharge occur. The spatial and temporal coherence of these climate trends suggests that warming and drying in the South Atlantic may be important contributors to the significant declines in streamflow that have been observed.

Prior to 1970, streamflow trends in the South Atlantic showed significant decreases throughout the northern portions of our study area, and few significant increases in the southern portion of the study area (Figure 2.3B). Temperatures declined significantly during this time period throughout the region (Figure 2.5B). Significant precipitation trends, though sparse, paralleled the spatial pattern of streamflow trends with decreasing precipitation in the north and increasing precipitation in the south (Figure 2.7B). Thus, the directionality and spatial distributions of streamflow trends were co-located in space with precipitation trends that favor the directionality of observed streamflow changes.

2.6.1 Atlantic Multi-decadal Oscillation Climatic Driver

The abrupt change in precipitation and streamflow in the 1970's has been noted throughout the conterminous United States (Krakauer and Fung, 2008; McCabe and Wolock, 2002). The cause of this shift is not known, although some studies have hypothesized that the change in streamflow is due to a change in precipitation patterns brought about by multiple factors, including a phase shift in the Atlantic Multi-decadal Oscillation (AMO; Krauker and Fund, 2008; Baines and Folland, 2007; Enfield, 2001). The AMO is a low frequency climate pattern linked to oscillations in sea surface temperature.

The AMO has a 60 to 110 year oscillation between colder and warmer SSTs that has alternatively disguised and accentuated global climate trends (Enfield et al., 2001). Since one complete oscillation of the AMO exceeds 60 years, the longest available streamflow records in the South Atlantic capture at most one complete cycle; thereby, making it difficult to distinguish long-term trends from low frequency climatic variation. The AMO switched from a warm phase to a cold phase around 1970 (McCabe et al., 2004), which corresponds to the timing of observed trends transitioning between the Mid- and Late-20th Century. The cooler temperatures during the Mid-20th Century (Figure 2.6C) are anticipated with the AMO warm phase because of its impact on the North Atlantic Oscillation (NAO; pressure rather than temperature). During the AMO warm phase, the NAO pulls the jet stream farther south and introduces cool air into the South Atlantic, particularly during the winter months (Figure 2.6C; D'Aleo, 2008). The AMO warm phase is often associated with a decrease in summer precipitation for the conterminous U.S. (McCabe et al., 2008); which we observed in July during the Mid-20th Century (Figure 2.8C). In 1995, the AMO returned to a warm phase and is currently favoring a return to drier summer conditions in the South Atlantic.

The temporal coincidence of a climate transition with a regional shift in streamflow trends indicates that discrete changes in climate regimes can have important effects on surface water resources in the South Atlantic. However, if the AMO is largely responsible for driving the general climate observed in the South Atlantic, then water resource managers have a better sense for what streamflow is likely to do during certain months over several decades. For example, warmer winter conditions (Figure 2.6) and less rain in the spring (Figure 2.8) resulted in decreased streamflow during the winter and spring recharge period (Figure 2.4). On the other hand, the reality of AMO-driven climate and streamflow requires that we have the capacity and water infrastructure necessary for handling abrupt transitions between long periods of predominantly wet or dry conditions in the South Atlantic.

2.6.2 National Studies

The prevalence of significant decreasing precipitation and streamflow trends in the South Atlantic from 1970-2005 has not been highlighted in previous national scale studies (Table 2.4). However, Lins and Slack (2005) did note that the South Atlantic and Gulf Coast regions did not follow the predominant trends of increasing streamflow. Regional studies from the northeast US have contradicted national scale studies, reporting decreasing streamflow trends since 1970 (Table 2.4; Hayhoe et al. 2007; Zhu and Day, 2005). Discrepancies between national and regional scale studies reflect the high spatial and temporal variability of climate and hydrology, as well as the sensitivity of trends to the time period assessed. As the spatial scale of a study increases, it becomes more difficult to ensure that there are not factors (such as we observed over larger time periods in the South Atlantic) that are obscuring important trends. This implies the necessity of conducting studies at the scale of water management strategies being pursued.

2.6.3 Anthropogenic Factors

Anthropogenic activities can also have a variety of effects on streamflow, including water withdrawals, reservoir operation, and land use change. These changes greatly complicate the relationship between climate and streamflow. For example, in Figure 2.3A there is an outlier in NC where streamflow continuously increased from 1934-2005 regardless of climate trends. Closer examination revealed that this stream is located in a small, rapidly urbanizing basin (38 km^2). Over 67% of the basin was classified as developed in 2006. Urbanization is considered one of the most dominant factors in altering streamflow and often results in increased streamflow after rain events due to increased impervious surface, but it can also result in an overall decrease in streamflow as groundwater recharge is inhibited (Hodgkin et al., 2007; Dewalle et al., 2000).

Lettenmaier et al. (1994) proposed that where streamflow does not follow climatic indicators, the cause is likely anthropogenic. The South Atlantic has been exposed to population increases over the past few decades, which confounds climate-streamflow relationships since no streams are completely free of anthropogenic influences (Hirsch, 2011; Wang and Hejazi, 2011). However, trends observed at HCDN sites were similar in number and magnitude to trends observed at non-HCDN sites (Table 2.1). While human activities may mask or amplify climate effects, we see limited evidence based on data from the HCDN network that anthropogenic activities are systematically altering streamflow in the South Atlantic.

2.6.4 Implications for Water Management and Policy

Water infrastructure and institutions in the South Atlantic have been constructed with a foundational assumption that climate, and therefore streamflow, is stationary (Hirsch 2011; Frederick and Gleick, 1999). However, the last few decades have challenged that assumption. Our findings indicate that stationarity is the exception and not the rule in the South Atlantic. Moreover, not only does streamflow commonly exhibit gradual drift over long periods of time, but also these trends can be punctuated by abrupt and large shifts associated with changes in climate regime. Thus managers and water infrastructure must be capable of handling these very different types of change in coming decades.

The presence of both persistent wetter and drier periods has important implications for water resource. For instance, Enfield et al. (2001) pointed out that streamflow in Florida to Lake Okeechobee was 40% higher from 1930-1964 than 1964-1994, representing a different hydrologic state that translated into a near complete reversal in water management priorities as they shifted from flood to drought management. While our annual streamflow changes are not of this magnitude, it is clear that there are periods of wetter and drier streamflow resulting in the need for accordant management practices, such as conservation prioritization, to shift over multi-decadal time periods.

Water managers in the South Atlantic are becoming more efficient in managing the immediate juxtaposition of wet months (e.g. recharging reservoirs in the winter) to dry months (e.g. mandatory water restrictions in the summer) within a year. However, the institutional capacity to manage persistent conditions of wet and dry years of streamflow has not widely developed in the South Atlantic. Institutions must have the capacity to shift orientation from flood protection to water conservation, and not become ensconced in prioritizing one strategy over the other. Undoubtedly, water resource managers are faced with significant distribution challenges associated with changing streamflow conditions. Our results show the flexibility to adapt to alternate, juxtaposed hydrologic conditions that may persist for several years is needed.

2.7 Acknowledgements

This study was funded by the Morris K. Udall Dissertation Completion Fellowship and further supported by the National Periship Award to Patterson. This work was also supported in part by an IPA from the US Army Corps of Engineers - Institute for Water Resources to Lutz and Doyle. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Morris K. Udall and Stewart L. Udall Foundation or the Corps of Engineers.

2.8 Tables

Table 2.1: SMK test results for streamflow. The number of significant trends is provided above the average change in streamflow from the start to end of the time period +/- standard deviation (cm). Results are subdivided by HCDN classification.

	Number of Sites		Significant Increase (cm)		Significant Decrease (cm)	
	HCDN	*Not HCDN*	*HCDN*	*Not HCDN*	*HCDN*	*Not HCDN*
Entire Record (1934-2005)	26	28	1 0.60±(N/A)	1 1.09±(N/A)	1 -0.50±(N/A)	6 -0.69±(0.20)
Mid-20th Century (1934-1969)	26	28	3 0.73±(0.15)	1 0.83±(N/A)	13 -0.99±-(0.48)	17 -0.80±(0.40)
Late 20th Century (1970-2005)	26	28	0	0	14 -0.96±(0.49)	12 -1.32±(0.76)

Table 2.2: SMK test results for temperature. The number of significant trends is above the average change in temperature from the start to end of the time period +/- standard deviation (^oC).

Time Period	Sites	Significant Increase (^oC)	Significant Decrease (^oC)
Entire Record (1934-2005)	60	7 0.52±(0.19)	36 -1.00±(0.56)
Mid-20th Century (1934-1969)	60	0	49 -1.27±(0.56)
Late 20th Century (1970-2005)	60	27 0.72±(0.25)	9 -0.76±(0.22)

Table 2.3: SMK test results for precipitation. The number of significant trends is provided above the average change in precipitation from the start to end of the time period +/- standard deviation (cm).

Time Period	Sites	Significant Increase (cm)	Significant Decrease (cm)
Entire Record (1934-2005)	90	8 1.85±(0.73)	2 -1.43±(0.25)
Mid-20th Century (1934-1969)	90	6 1.83±(0.22)	5 -1.77±(0.50)
Late 20th Century (1970-2005)	90	0	8 -1.69±(0.43)

Table 2.4: Highlighted results from previous streamflow trend studies.

Author	Data	Spatial Scale	Temporal Scope	Main Trend Direction	Notes
Andreadis & Lettenmaier (2006)	Annual HCDN streamflow	National	1925-2003	Increase	Linked to precipitation.
Arrigoni et al. (2010)	Daily USGS streamflow	Northern Rocky Mountains	1950-2008	None	Cyclical pattern from climate. Anthropogenic factors drove streamflow trends, not climate.
Douglas et al. (2000)	Annual max and min HCDN streamflow	National	1959-1988 1939-1988	Increase in min and med flow	Trends present in Midwest region of U.S. Present at both time scales.
Krakauer & Fung (2008)	Annual HCDN streamflow	National	1920-2007	Increase	Most increase due to abrupt shift in 1960's. Linked to precipitation.
Hayhoe et al. (2007)	USGS streamflow	Northeast US	1950-2000 1970-1999	Slight increase Slight decrease	Linked to temperature increase and little change in precipitation.
Hodgkins et al. (2007)	Monthly USGS streamflow	Great Lakes Basin	1915-2004	Low 1955-1970 High 1970-1995	Linked to precipitation.
Lettenmaier et al. (1994)	Monthly HCDN streamflow	National	1948-1988	Increased in Midwest Decreased in NE	Strong seasonal variation in all variables. Some correlation with precipitation. Temperature increased.
Lins & Slack (2005)	Annual min, med and max HCDN streamflow	National	1940-1999	Increase in low to med. flows in central US	No systematic monthly trends. Linked to precipitation. SE-Gulf had noticeable differences with more decreasing trends.
McCabe & Wolock (2002)	Annual min, med & max HCDN streamflow	National	1941-1999	Increase in min and med flow	Step increase ca. 1970. Linked to precipitation.
Small et al. (2006)	HCDN streamflow	Eastern US	1948-1997	Increase in min and med flow	Linked to increase in fall precipitation
Wang & Hejazi (2011)	International Model Parameter Estimation Experiment	National	1948-2003	Increase (largely in Midwest)	Climate linked to increasing streamflow. Anthropogenic factors have spatially heterogeneous impacts.
Zhu & Day (2005)	USGS streamflow	PA	1971-2001	Decrease	Greatest decrease in June, July, and December.
This study	Monthly USGS streamflow	South Atlantic	1934-2005, 1934-1969, 1970-2005	None Decrease Decrease	Linked to precipitation.

2.9 Figures

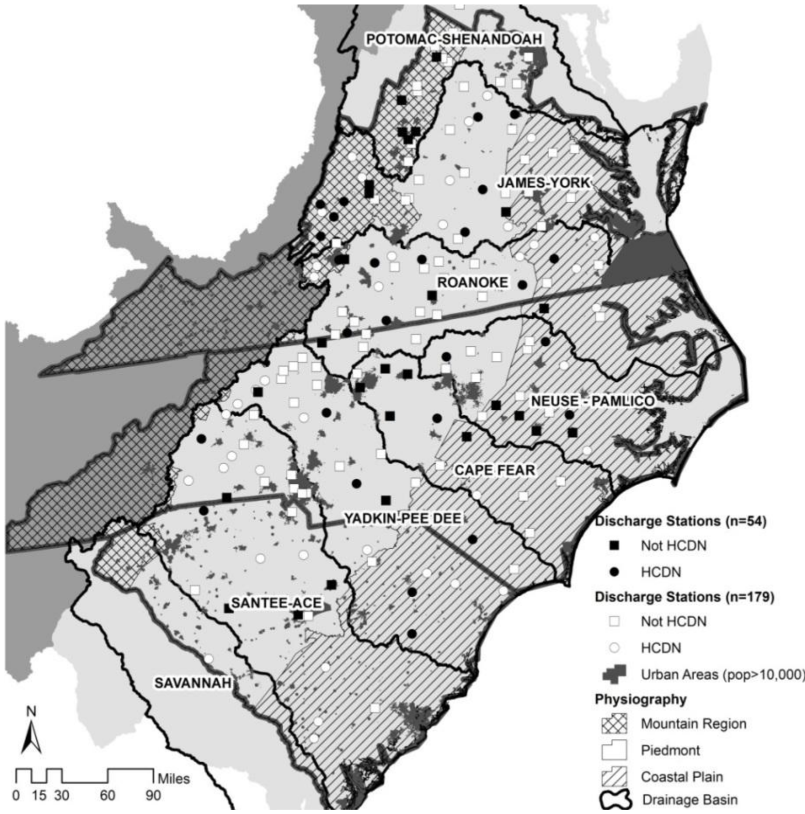


Figure 2.1: The South Atlantic Region with physiographic provinces intersecting NW to SE Atlantic draining basins.

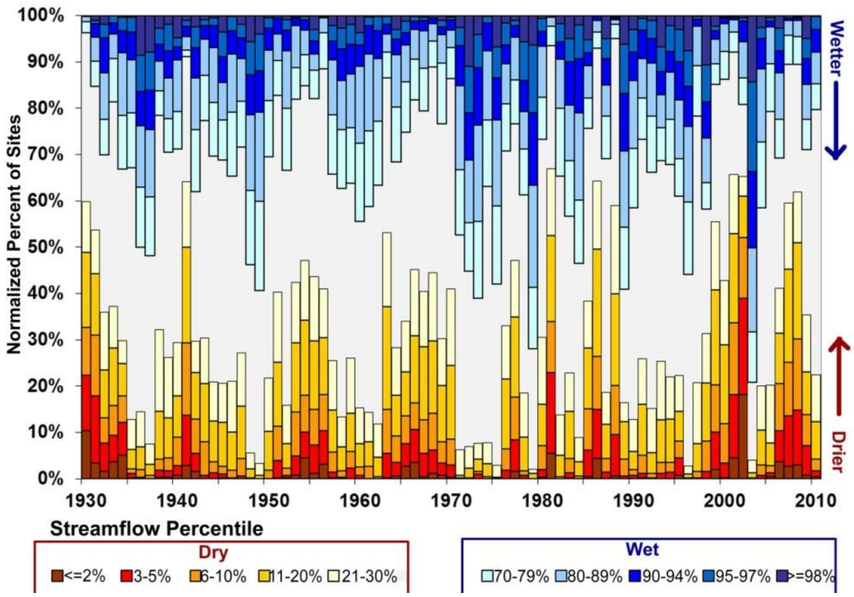


Figure 2.2: Percent of months for each site (12 months * 54 sites) per year that are dry (<= 30% average streamflow) and wet (>= 70% average streamflow). Darker shades of red (blue) indicate drier (wetter) the conditions.

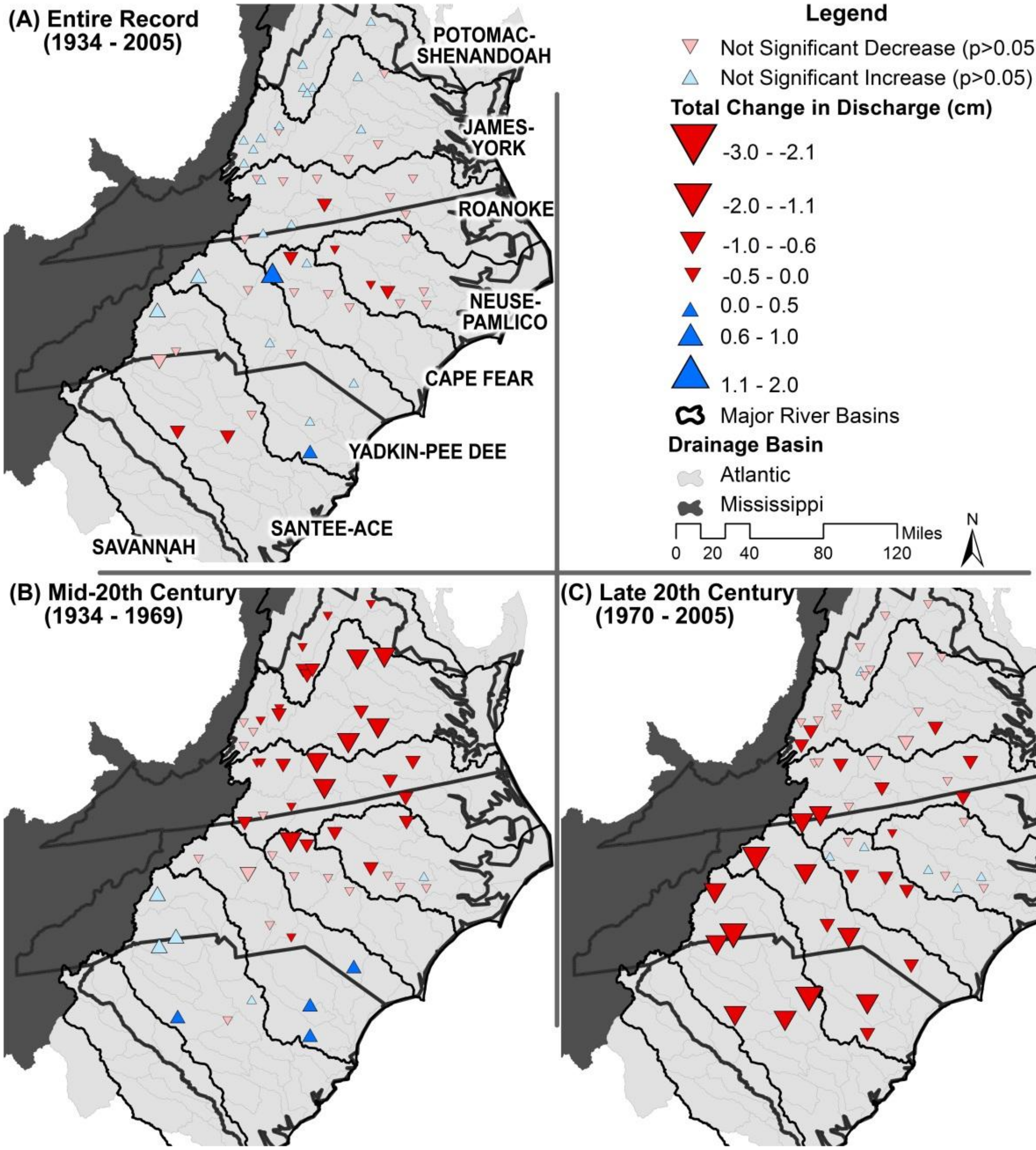


Figure 2.3: Spatial distribution of streamflow trends. Triangles point in the direction of the trend. Size reflects the magnitude of the change over the time period (A) Entire record. (B) Mid-20th Century. (C) Late-20th Century.

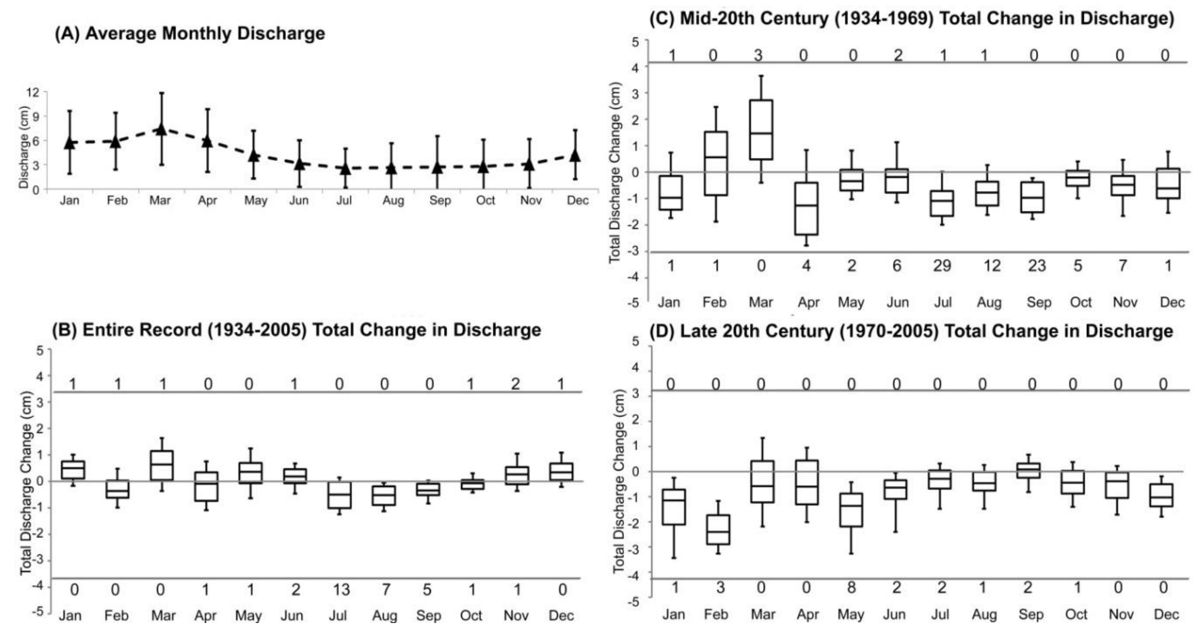


Figure 2.4: (A) Average monthly streamflow for stations. (B-D) Box plot of changes in streamflow for all time periods. Box shows the 25th, 50th, and 75th percentiles. Bars show the 10th and 90th percentiles. The number of significant sites with trends in streamflow for each month are shown above (increasing) and below (decreasing) the boxplots.

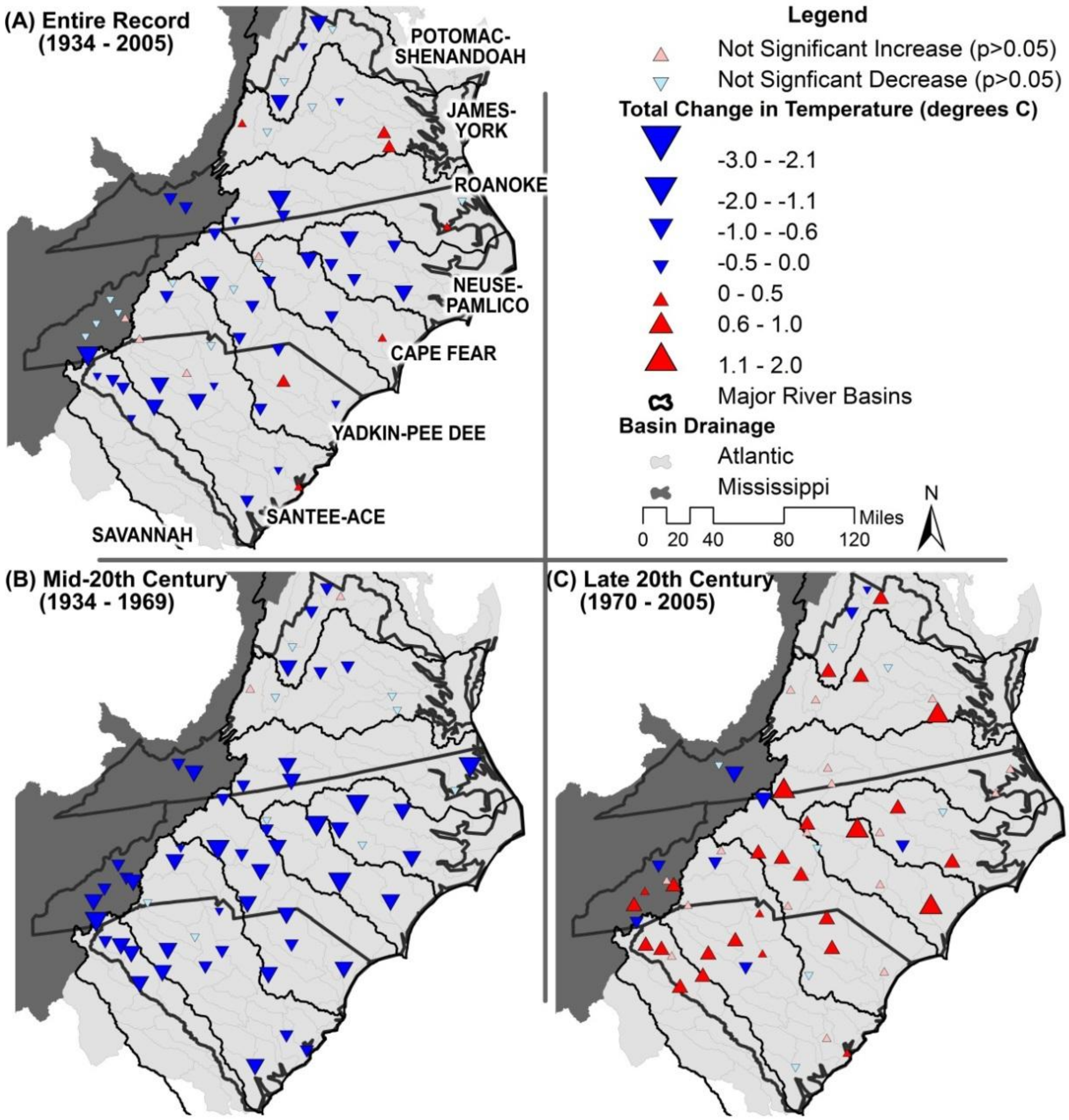


Figure 2.5: Spatial distribution of temperature trends. Triangles point in the direction of the trend. Size reflects the magnitude of the change over the time period. (A) Entire record. (B) Mid-20th Century. (C) Late-20th Century.

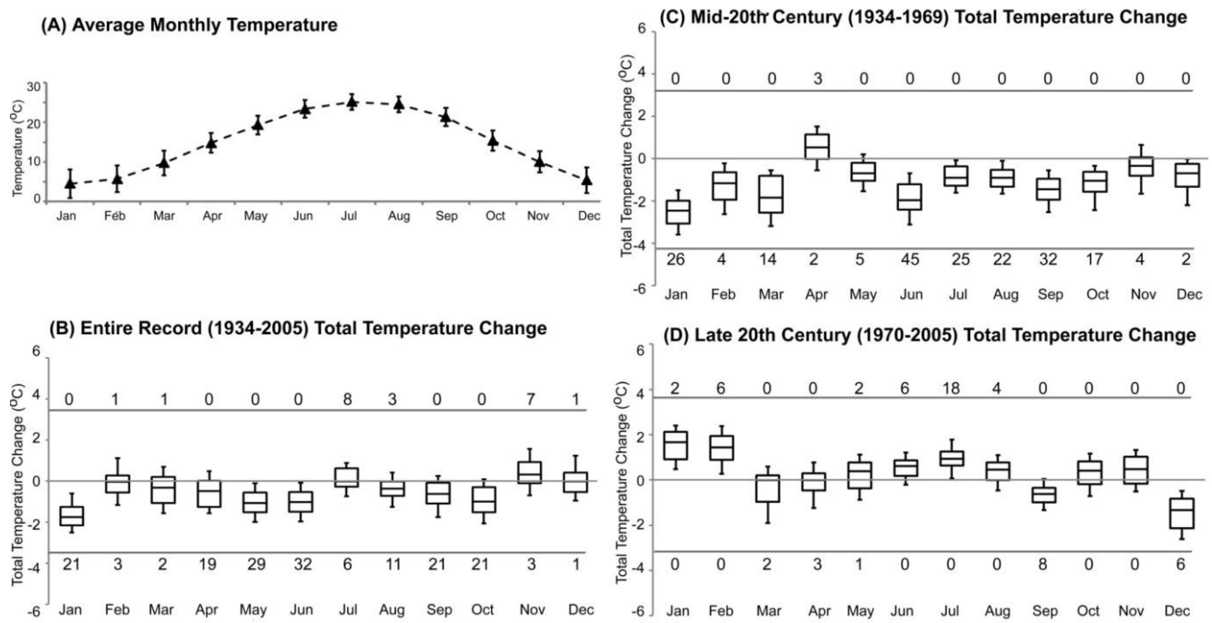


Figure 2.6: (A) Average monthly temperature for stations. (B-D) Box plot of changes in temperature for all time periods. Box shows 25th, 50th, and 75th percentiles. Bars show 10th and 90th percentiles. The number of significant stations with trends in temperature are provided above (increasing) and below (decreasing) each monthly boxplot.

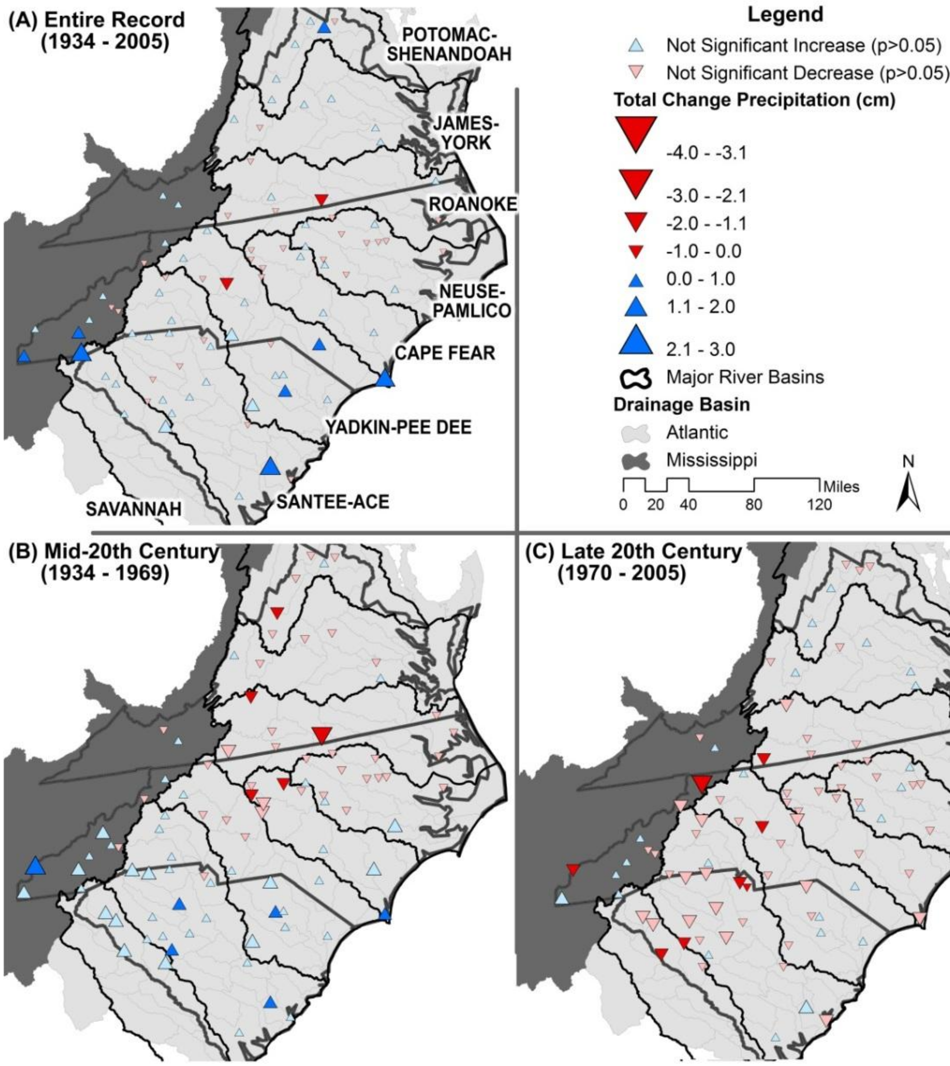


Figure 2.7: Spatial distribution of precipitation trends. Triangles point in the direction of the trend. Size reflects the magnitude of the change over the time period. (A) Entire record. (B) Mid-20th Century. (C) Late-20th Century.

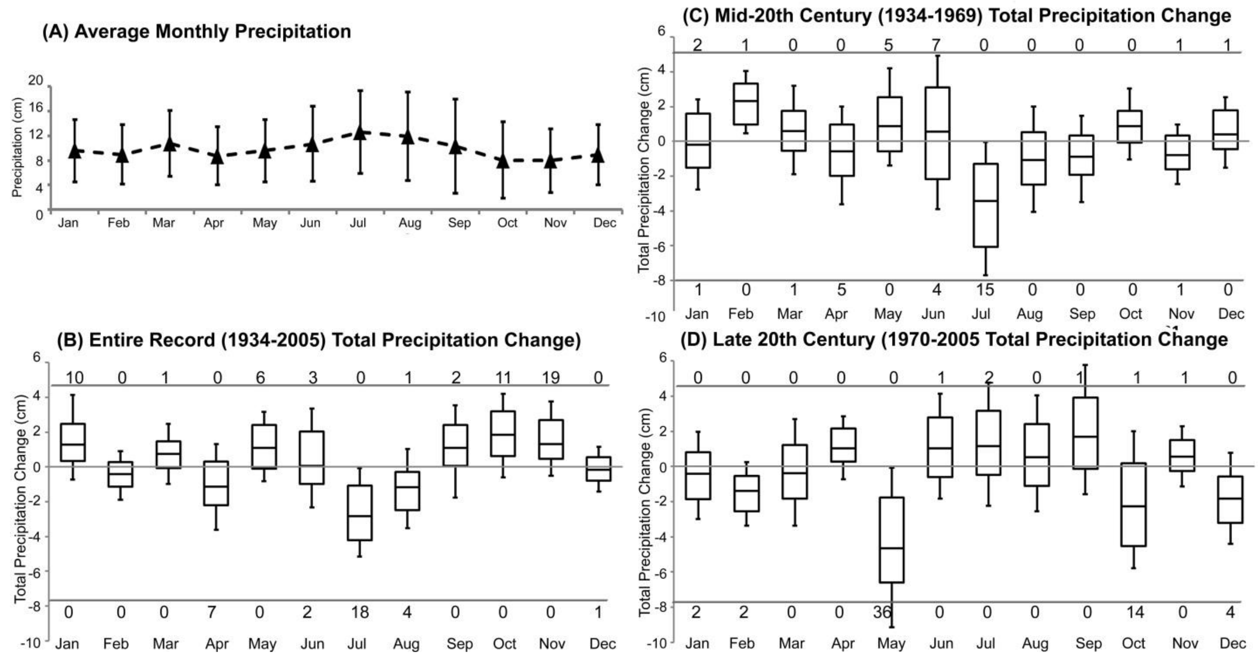


Figure 2.8: (A) Average monthly precipitation for stations. (B-D) Box plot of changes in precipitation for all time periods. Box shows 25th, 50th, and 75th percentiles. Bars show 10th and 90th percentiles. The number of significant stations with trends in precipitation are provided above (increasing) and below (decreasing) each monthly boxplot.

2.10 Literature Cited

Andreadis, K.M. and D.P. Lettenmaier. 2006. Trends in 20th Century Drought over the continental United States. *Geophysical Research Letters* 33 (L10403), doi: 10.1029/2006GL025711.

Anselin, L. 1995.Local Indicators of Spatial Association – LISA. *Geographical Analysis* 27 (2): 93-115.

Arrigoni, A.S., M.C. Greenwood, and J.N. Moore. 2010. Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of river in the Northern Rocky Mountains, United States. *Water Resources Research* 46 (W12542), doi:10.1029/2010WR009162.

Band, L.A. and D. Salveson (Eds). 2009. Climate Change Committee Report. UNC Institute for the Environment at the University of North Carolina, Chapel Hill. pp. 197.

Baines, P.G. and C.K. Folland. 2007. Evidence for a rapid global climate shift across the late 1960's. *Journal of Climate* 20: 2721-2744, doi: 10.1175/JCLI4177.1

Blowe, B., S. Harrell, F. Akhtar, C. Cannady, and J. Crews-Klein. 2006. Water 2030 Series. The North Carolina Rural Center. http://www.ncruralcenter.org *Last Accessed September 2011*.

D'Aleo, J. 2008. The Atlantic Multidecadal Oscillation. Intellicast.com – The Authority in Expert Weather. http://www.intellicast.com/Community/Content.aspx?a=127. *Last Accessed August 5, 2011.*

DeWalle, D.R., B.R. Swistock, T.E. Johnson, and K.J. McGuire. 2000. Potential effects of climate change and urbanization on mean annual streamflow in the United States. *Water Resources Research* 36: 2655-2665.

Douglas, E.M., R.M. Vogel, and C.N. Kroll. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* 240: 90-105.

Campbell, J.L., C.T. Driscoll, A. Pourmokhatarian, and K. Hayhoe. 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brooke Experimental Forest, New Hampshire, United States. Water Resources Research 47 (W02514), doi: 10.1029/2010WR009438.

Claessens, L., C. Hopkinson, E. Rastetter, and J. Vallino. 2006. Effect of historical changes in land use and climate on the water budget of an urbanizing watershed. *Water Resources Research* 42 (W03426), doi: 10.1029/205WR004131.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 28 (10): 2077-2080.

Frederick, K.D. and P.H. Gleick. 1999. Water and Global Climate Change: Potential Impacts on U.S. Water Resources. Pew Center on Global Climate Change. Washington, D.C.

Granato, G.E. 2006. Kendall-Theil Robust Liine (KTRLine-version 1.0) – A visual basic program for calculating and graphing robust nonparametric estimates of linear-regression coefficients between two continuous variables: Techniques and Methods of the U.S. Geological Survey, book 4, chap. A7, 31 p.

Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T.J. Troy, D. Wolfe. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. *Clim Dyn* 28: 381-407, doi: 10.1007/s00382-006-0187-8.

Hirsch, R.M. 2011. A perspective of Nonstationarity and Water Management. *JAWRA* 47 (3): 436-446. DOI: 10.1111/j.1752-1688.2011.00539.x

Hirsch, R.M. and Slack, J.R. 1984. A Nonparametric Trend Test for Seasonal Data with Serial Dependence. *Water Resources Research* 20 (6), pp. 727-732.

Hodgkins, G.A., R.W. Dudley, and S.S. Aichele. 2007. Historical changes in precipitation and streamflow in the U.S. Great Lakes Basin, 1915-2004: U.S. Geological Survey Scientific Investigations Report 2007-5118. p31.

Krakauer, N.Y. and I. Fung. 2008. Mapping and attribution of change in streamflow in the coterminous United States. *Hydrol. Earth Syst. Sci* 12: 1111-1120.

Lettenmaier, D.P., E.F. Wood, J.R. Wallis. 1994. Hydo-climatological trends in the continental United States, 1948-88. *Journal of Climate* 7: 586-607.

Lins, J.F. and H.R. Slack. 2005. Seasonal and Regional Characteristics of U.S. Streamflow Trends in the United States from 1940 to 1999. *Physical Geography* 26 (6): 489-501.

McCabe, G.J., J.L. Betancourt, S.T. Gray, M.A. Palecki, and H.G. Hidalgo. 2008. Associations of multi-decadal sea-surface temperature variability with US drought. *Quaternary International* 188: 31-40, doi:10.1016/j.quaint.2007.07.001.

McCabe, G.J., M.A. Palecki, and J.L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *PNAS* 101 (12): 4136-4141, doi: 10.1073/pnas.030678101.

McCabe, G.J. and D.M. Wolock. 2002. A step increase in streamflow in the conterminous United States. *Geophysical research Letters* 29 (24), 2185, doi: 10.1029/2002GL015999.

Milly, P.C.D., J. Betancourt, M. Fallenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319 (5863): 573-574, doi: 10.1126/science.1151915

Small, D., S. Islam, and R.M. Vogel. 2006. Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? *Geophysical Research Letters* 33, L03403, doi: 10.1029/2005GL024995.

Smith, J.A., M.L.Baeck, J.E. Morrison, P. Sturdevant-Rees, D.F. Turner-Gillespie, P.D. Bates. 2002. The regional hydrology of extreme floods in an urbanizing drainage basin. *Journal of Hydrometeorology* 3, 267-282.

Sun, G., S.G. McNulty, J. Lu, D.M. Amatya, Y. Liang, R.K. Kolka. 2005. Regional annual water yield form forest lands and its response to potential deforestation across the southeastern United States. *Journal of Hydrology* 308: 258-268, doi:10.1016/j.jhydrol.2004.11.021

Wachob, A., A.D. Park, and R. Newcome,Jr. (eds). 2009. South Carolina State Water Assessment 2nd edition. South Carolina Department of Natural Resources, Columbia, SC. http://www.dnr.sc.gov/water/hydro/HydroPubs/assessment.htm. *Last Accessed September 2011.*

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47, W00J12, doi: 10.1029/2010WR010283.

Zhu, Y. and Day, R.L. 2005. Analysis of streamflow trends and the effects of climate in Pennsylvania, 1971 to 2001. *JAWRA* 41 (6): 1393-1405.

CHAPTER 3

CLIMATE AND DIRECT HUMAN CONTRIBUTIONS TO CHANGES IN MEAN ANNAUL STREAMFLOW[2]

3.1 Abstract

Streamflow changes in response to external climate controls and human impacts within a basin (such as reservoirs, urbanization, withdrawals, and irrigation). Understanding how climate and human impacts have contributed to changes in streamflow provides important information regarding how to effectively and efficiently address and anticipate changes in water availability. We used Budyko curves to ascribe changes in streamflow due to climate and human factors between two time periods in both natural and human modified basins in the South Atlantic, US. A Budyko curve was calculated for each watershed to describe the average climate control on a watershed given its land cover during the period 1934-1969. We then assessed how changes in climate versus changes in human factors contributed to alter streamflow during the period 1970-2005. We found climate contributed to increased streamflow throughout the South Atlantic since the 1970's; whereas, human factors varied between basins and either amplified (increased) or minimized (decreased) the climate change effect on streamflow. Human impacts were equivalent to, or greater than, climate impacts in 43% of our watersheds. Non-metric Multidimensional Scaling Analysis and

---

[2] Chapter 3 was co-authored with B. Lutz and M.W. Doyle and will be submitted to WRR

correlations found total reservoir storage and population density were significantly and negatively correlated with streamflow.

3.2 Introduction

3.2.1 Drivers of Streamflow Change

Streams are an important source of water supply and provide 65±20% of the water used for residential and irrigation purposes in a selection of Atlantic drainage basins within Virginia (VA), North Carolina, (NC), and South Carolina (SC; hereafter the 'South Atlantic'; USGS, 2005). Changes in streamflow have a direct impact on available water supply; however, there are often limited information regarding the degree to which climate or human factors are contributing to regional changes in streamflow.

In the absence of human activity, climate is the primary determinant of streamflow (Campbell, 2011). While humans can indirectly impact streamflow through changing climate patterns (e.g. urban heat islands), human activities often directly change the landscape and the processes controlling water movement through catchments. In the United States, important streamflow changes in response to both exogenous climate controls and endogenous catchment processes have been documented. Studies that have focused on catchments with minimal human impact have reported that a shift towards greater precipitation in the 1970s resulted in an abrupt increase in streamflow (e.g. Krakauer and Fung, 2008; Lins and Slack, 2005; McCabe and Wolock, 2002). Other studies that have included basins impacted by human activities have found greater changes in streamflow than can be attributed to climate change alone (e.g. Wang and Hejazi, 2011; Arrigoni et al., 2010). Both climate and anthropogenic factors (used interchangeably with "human") may contribute to monotonic, as well as abrupt, changes in streamflow (Hirsch, 2011; Stakiv, 2011). If we can better understand the roles of exogenous climate controls versus endogenous anthropogenic influences on streamflow within a basin, it may be possible to better anticipate and prepare for projected changes in climate and human activities.

The key climate descriptors influencing streamflow are precipitation and temperature, with the latter manifested largely through altered evapotranspiration rates (Trenberth, 2011; Vörösmarty et al., 2000). Long-term trends in climate are difficult to detect because of persistence, which is the phenomenon of wet years following wet years and dry years following dry years (Hirsch, 2011). The persistence of multi-decadal hydrologic states (wet or dry) may be driven by low frequency changes in sea surface temperatures (SST) that drive global weather patterns. For example, the Atlantic Multidecadal Oscillation (AMO) is a 60 to 110 year oscillation of SST in the Atlantic Ocean that has been linked to changes in streamflow volume (Perlwitz et al., 2009; McCabe et al., 2008; Tootle et al., 2005; Enfield et al., 2001). In the United States, warmer AMO phases are linked to drier conditions (McCabe et al., 2008).

In addition to cyclic hydrologic states, several studies predict that climate may produce an underlying linear trend in streamflow changes as a progressively warmer climate speeds up the hydrologic cycle (e.g. Trenberth, 2011; Hungtington, 2006). The Clausius-Clapeyron equation states that warmer air leads to greater evaporation and an increased capacity to hold more water vapor in the atmosphere; thereby, producing about a 7% increase in precipitation for every $1^{o}C$ rise in temperature (Allen and Ingram, 2002). In reality, the Clausius-Clapeyron relationship is substantially smaller as evaporation becomes energy limited (Hungtington, 2006). This hypothesis is supported by the nation-wide observations that precipitation has increased since the 1970's as the global air temperature has increased (e.g. Krakauer and Fung, 2008). Thus, changes in streamflow can be attributed to linear, cyclic, or a combination of these (or other) climatic drivers that occur at local, regional, or global scales.

Anthropogenic activities may influence streamflow through large-scale infrastructure (i.e. reservoirs; Graf, 1999), water withdrawals (Vörösmarty et al., 2000), and land use change that impacts groundwater recharge and evapotranspiration (i.e. deforestation, reforestation, urbanization, agriculture; Claessens et al., 2006). Changes in streamflow in adjacent basins with similar climates can be significantly different depending on differences in anthropogenic activities.

Reservoirs are explicitly designed to control streamflow for multiple purposes, including flood control, water supply, hydropower generation, and recreation. Reservoir management often reduces variability within the hydrograph on an annual and inter-annual basis by reducing high flows and increasing low flows (Poff et al., 2007). In addition, reservoirs serve as a catalyst for land cover change (i.e. flood control enables nearby urbanization while increased water supply enables population and agricultural expansion; Degu et al., 2011). Growing populations increase water withdrawals and can have a significant impact on streamflow (Weiskel et al., 2007). River basins with high demand but low supply might transfer water from a basin with high supply but low demand; thereby, linking and redistributing water between otherwise independent river basins. Growing populations are also tied to increasing urbanization and deforestation. Urban land cover is considered to be a dominant factor in altering hydrology due to vegetation removal (decreases evapotranspiration; E) and increased impervious surfaces (prevents groundwater recharge and increases storm runoff; Claessens et al., 2006). This often results in greater streamflow variability (Kauffman and Vonk, 2011). Changes in forest cover can greatly impact streamflow (Q) as reforestation increases E (decreases Q) and deforestation decreases E (increases Q; Kim, Forthcoming; Nisbet, 2005; Sun et al., 2005).

3.2.2 Previous Studies Attributing Climate and Human Influences to Streamflow

In many catchments, both climate and human impacts have changed through time, making it difficult to separate the contributions of climate and humans to streamflow changes. Some studies have compared nearby natural and human modified basins using linear and non-linear models. Changes in streamflow in natural basins are attributed to climate and any difference in the human-modified basin is attributed to human influences. The type of human influence in a basin is often broadly categorized as having high reservoir storage, irrigation, or urbanization relative to the other basins in that particular study. For example, Arrigoni et al. (2010) found direct anthropogenic modifications (mainly damming and irrigation) of streamflow in the Northern Rocky Mountains to have reduced the variation in daily and annual discharges relative to nearby natural basins. A study by Hodgkins et al. (2007) in the Great Lakes region found climate to have a greater impact on streamflow than human modified basins, with agricultural and urbanizing basins contributing to a significant increase in minimum streamflow.

Other studies use a combination of empirical analysis and physical based models to determine whether human activities account for major changes in streamflow within a specific watershed. Kim's (Forthcoming) hydrologic model had approximately a 100 mm deficit from observed streamflow for the Flat River basin in North Carolina between 1920 and 1970. During this time agricultural lands were reforested and after the mid-1970's, when reforestation had peaked, the modeled and observed streamflow were similar. In contrast, Claessens et al. (2006) found climate to have a greater role in changing evapotranspiration rates than human-induced land use changes (largely the conversion of forest to sub-urban land cover) in a Massachusetts watershed.

The above studies highlight how the relative contribution of climate and human induced changes to streamflow differ depending on the location and time period of observation. In many cases there is neither a comparable adjacent basin free of human impact for conducting a paired study, nor is there a sufficient amount of data for using physical based empirical models. However, Wang and Hejazi (2011) developed a method for quantifying the relative contribution of climate and direct anthropogenic modifications on mean annual streamflow between two time periods. The method relies on Budyko curves (described in detail below), which present the interdependence between mean annual evaporation and potential evaporation for the precipitation regime in a watershed. This method only requires data for precipitation, temperature, and streamflow (Budyko, 1974); which are available at a higher spatial and temporal resolution than most data for human activities. Differences in streamflow between the two periods can either be predicted based on the initial relationship between mean annual precipitation, evaporation, and potential evaporation as defined by the Budyko curve, or can deviate from this prediction due to anthropogenic factors.

3.2.3 Study Objectives

Previously, Patterson et al. (Forthcoming) observed decreasing streamflow trends in the South Atlantic (Atlantic draining basins in North Carolina (NC), South Carolina (SC), and Virginia (VA)) during two time periods and two different hydrologic states: a drier 1934-1969 and a wetter 1970-2005. While a regional shift in streamflow consistent with changing climate regimes was observed, several of the basins have also been heavily modified by human activities that include reservoir construction, urbanization, and reforestation. In this paper, we applied the methods of Wang and Hejazi (2011) to quantify the relative contribution of climate and anthropogenic factors to changes in mean annual streamflow for basins in the South Atlantic. We then related basin properties (land cover, population growth, reservoir storage, and water demand) to the magnitude and direction of the estimated human contribution driving streamflow change. Our goal was to assess whether different anthropogenic influences consistently had the same impact on streamflow in order to inform ongoing water policy discussions.

3.3 Study Area

We previously examined trends in streamflow volume at 54 stream gauges within 24 separate basins in the South Atlantic (the remaining 30 stream gauges are nested within those basins; Figure 3.1A; Patterson et al., Forthcoming). Basins are labeled from north (Basin 1) to south (Basin 24). The largest catchment of a nested set is given an integer value, while hierarchically nested sub-basins are denoted with decimal places. For example, basin 17.21 drains into Basin 17.2, which drains into Basin 17.

Only 23 of the 54 stream gauges in our prior study had climate data available from 1934-2005 (Figure 3.1A; Table 3.1) and will be used here. A Non-metric Multidimensional Scaling Analysis (NMS) confirmed that the selected basins captured the environmental variability of the entire study area (results not shown).

The South Atlantic has a humid-subtropical climate (Degu et al., 2011) and three main physiographic provinces (Figure 3.1). The Coastal Plains are predominantly flat and extend from the Atlantic coast to the fall line. Rivers are wide and slow moving, forming estuaries that extend far inland. Soils in the Coastal Plain are ideal for agriculture and groundwater use is prevalent (Figure 3.2B). The population in the Coastal Plains is predominantly rural with a few military and tourist cities located along the coast. The Piedmont extends from the fall line to the foothills of the Appalachian Mountains. Elevation ranges from under 100 m in the east to over 300 m in the west. This rolling topography is ideal for development and the landscape has become mosaic of forest, agriculture, and urban centers (Figure 3.2D). The Piedmont underwent extensive cropland reversion during the early to Mid-20th Century as row crops were replaced by forest and pasture (Trimble and

Weirich, 1987). The landscape has continued to change since the 1970's with rapid population growth (over 30% per decade in some counties) in both North and South Carolina that have led to conversion of some agricultural land to suburban developments (Figure 3.2A). The Piedmont has also been a location of historic and recent reservoir construction, dating from the textile mills of the 19th century to flood control, drinking water, and hydro-electric reservoirs in the late 20th century. The Mountain Region consists of the Appalachian Mountain range and has wide variability in both temperature and precipitation due to orographic effects. Snowfall can be significant in this region, although it generally accounts for less than 25% of annual precipitation. The Mountain Region is predominantly forested and sparsely populated with population centers located in river valleys. Tourism, forestry, and agriculture are the economy driving industries. Many of these rural communities rely on groundwater for their water supply.

3.4 Methodology

In this paper, we applied the Budyko decomposition method derived by Wang and Hejazi (2011) to estimate the relative contribution of climate- and human-induced changes to mean annual streamflow for 23 basins located in the South Atlantic. We then explored the combined interaction of land cover types, population, water demand, and reservoir storage on the direction and magnitude of human-induced streamflow changes using a Non-metric Multidimensional Scaling (NMS) analysis. Lastly, we applied simple linear regression to assess the relationship between discrete anthropogenic activities and the human-induced change in streamflow.

3.4.1 Budyko Analysis

The volumetric water budget for a river basin can be simplified as: $\Delta Q = \Delta P - \Delta E - \Delta S$; whereby ΔQ is the change in streamflow; ΔP is the change in precipitation, ΔE is the change in evapotranspiration, and ΔS is the change in watershed storage (groundwater, vegetation, etc.). In catchments with minimal human impact, we can assume that over many years the mean $\Delta S = 0$. However, diversion of water for human uses makes this a poor assumption for some basins in the South Atlantic (Table 3.1) that have experienced significant population growth and land use change (Figure 3.2), as well as increased reservoir water management (Figure 3.4). Thus, we required a method for isolating the effects of ΔE and ΔS.

<u>The Budyko Hypothesis</u>

Budyko (1974) developed a framework that linked climate to the relationship between streamflow and evapotranspiration in large basins (>1,000 km^2) averaged over long time periods (>>1 year; Donohue et al., 2007). The large area and long-time period ensures the validity of the assumption that the ΔS is approximately zero (Donohue et al., 2007). The reliability of the Budyko curve is greatest when basin area exceeds 1000 km^2 (91% of our basins have an area greater than 900 km^2; Table 3.1).

Budyko (1974) essentially used basic physical principles to show that the long-term average ratio of mean annual evapotranspiration to mean annual precipitation (E/P) is largely controlled by the water-energy balance of a basin. The water-energy balance can be described as the long-term average ratio of mean annual potential evapotranspiration to mean annual precipitation (E_p/P; Wang and Hejazi, 2011); which is also referred to as the dryness index and is a measure of the maximum potential evapotranspiration possible given the basin's climate (Figure 3.3). In basins where $E_p/P<=1$, energy (or temperature) is the limiting factor; whereas, in basins with an $E_p/P>1$, water supply (or precipitation) is the limiting factor. All basins in the South Atlantic were energy limited (E/P<=1; Figure 3.5).

Lu et al. (2005) recommended the Hamon method as the best temperature-based method for calculating stable and reasonable estimates of annual Ep at the watershed scale in the Southeast, US. The long-term average E_p (5 to 30 years) estimated by the temperature based Hamon equation was comparable to the solar-radiation based Priestley-Taylor method. The Hamon method incorporates location, month, day length, and average temperature to calculate the average monthly Ep for a basin (Appendix 3.10.1).

The observed evapotranspiration (E) is estimated as the long-term average precipitation minus streamflow (Donohue et al., 2007), and is a measure of the ability of the basin to evaporate water. The Budyko hypothesis proposes that the empirical relationship between the average E/P and Ep/P for most catchments fit along a unique curve, which has been re-formalized by Fu (1981):

Equation 3.1

$$\frac{E}{P} = 1 + \frac{E_p}{P} - [1 + \left(\frac{E_p}{P}\right)^w]^{1/w}$$

Where P is the annual precipitation, E is the actual annual evapotranspiration, E_p is potential annual evapotranspiration, and w is a single value related to the complex interaction between vegetation type, soil properties, and topography (Ma et al., 2008). Evapotranspiration is most sensitive to variation in w for climates with a dryness index ~1 and becomes decreasing sensitive moving away from the transition between energy and water-limited basins (Zhang et al., 2004). Higher values of w are typical for landscapes that favor evapotranspiration processes (e.g. heavily forested basins), whereas lower values of w are indicative of basins whose characteristics do not favor evapotranspiration (Donohue et al., 2007; Zhang et al., 2004; Zhang et al., 2001). Thus, each watershed has a slightly different Budyko curve representing the unique watershed characteristics present in that basin, such as water storage (Milly, 1994), land cover (Zhang et al., 2004), and anthropogenic management (Wang and Hejazi, 2011) that influences the relationship between evapotranspiration and precipitation.

Dramatic changes in land cover can change the relative proportions of Q and E, or the ability of the basin to evaporate water, which will ultimately change the position of a basin in the Budyko framework (Donohue et al., 2007). By comparing the relative change in the relationship of E/P to E_p/P for a basin between two time periods, we can see the impact of changes in climate and basin characteristics (assumed to be due to human changes given the relatively short time period) on evapotranspiration, and hence streamflow.

Budyko Decomposition Method

There are three components to using the Budyko curve for decomposing climate and human effects on streamflow (Wang and Hajazi, 2011). First, the relationship between average E/P and E_p/P ratios are calculated and plotted for each basin during an initial time period (E_1/P_1, E_{p1}/P_1). In this study, we used data from 1934-1969 (hereafter referred to as Period 1). We divided our data around 1970 because widespread changes in streamflow have been observed throughout the South Atlantic; thereby, providing an opportune case study where significant streamflow changes have been documented (Patterson et al., Forthcoming). The point (E_p/P, E/P) is a coordinate location that will hereafter be referred to as φ (psi). Thus, coordinate points plotted for Period 1 are represented as φ_1. A Budyko curve is derived for each site by fitting the w parameter to φ_1.

Second, we calculate mean E/P and E_p/P ratios (φ_2) for the period from 1970-2005 (Period 2; Figure 3.3). Third, we calculated the contributions of climate (ΔQ_C) and direct human (ΔQ_H) induced changes to streamflow for each basin by calculating the movement from φ_1 to φ_2. The method assumes that if climate changes between Period 1 and Period 2, the evaporation ratio (E_2/P_2) will move along the Budyko curve derived for that particular basin's initial characteristics (w parameter remains constant). Thus, ΔQ_C is the amount φ_2 moves left (increase in Q) or right (decrease in Q) along the Budyko curve. Any movement away from the Budyko curve is attributed to human influences (ΔQ_H), either below the curve (increase in Q) or above the curve (decrease in Q; Figure 3.3).

The climate change component of the evapotranspiration ratio (E_2'/P_2) is calculated using Fu's equation (Figure 3.3); whereby, $E_{p2}/P_2=E_p/P$ and w=the w parameter calculated for Period 1. The climate change contribution to streamflow (ΔQ_C) is:

Equation 3.2

$$\Delta Q_C = P_2(1 - \frac{E_2'}{P_2}) - Q_1$$

The magnitude of the direct human induced change to streamflow (ΔQ_H) is:

Equation 3.3

$$\Delta Q_H = P_2(\frac{E_2'}{P_2} - \frac{E_2}{P_2}),$$

The ΔQ_C plus the ΔQ_H equals the total change in mean annual streamflow (ΔQ) from Period 1 to Period 2. The climate- and direct human-induced percent change in mean annual streamflow between the two time periods were computed to simplify comparisons between basins (Wang and Hejazi, 2011).

Equation 3.4

$$\Delta C\% = \frac{\Delta Q_C}{Q_1} \qquad \Delta H\% = \frac{\Delta Q_H}{Q_1}$$

The Budyko decomposition method provides a single picture of the ΔQ_C and ΔQ_H between Period 1 and Period 2. However, climate and human impacts on streamflow are not stationary and their relative contributions will vary over time. Keeping Period 1 constant, we recalculated Period 2 into consecutive, overlapping 5 year intervals in order to better understand the temporal variation in ΔQ_C and ΔQ_H.This expanded our understanding of the interplay between human and climate factors and the rate at which these relative relationships can change.

Data Acquisition for Budyko Analysis

Monthly average discharge data were acquired from the United States Geologic Survey (USGS) stream gauge network (http://nwis.waterdata.usgs.gov/nwis). Gauges were included if they were operating between 1934 and 2005 and missing less than 10% of the record (n=23). Monthly streamflow was totaled to obtain mean annual streamflow (MAS). MAS was normalized by drainage area and converted into centimeters (cm). Five basins are part of the Hydro-Climatic Data Network (HCDN), which is a national dataset of USGS stream gauges largely free of anthropogenic influences including reservoirs, diversions, or major land use changes within the period of record (prior to 1988; Lins and Slack, 2005). We anticipate these basins to have a small Q_H component.

Monthly total precipitation and mean temperature data were obtained from the U.S. Historical Climatology Network (HCN) dataset developed by the National Climatic Data Center. HCN precipitation (n=46) and temperature (n=29) stations with continuous records from 1934-2005 were located within our study area. HCN data are adjusted for biases that develop due to changes in station location and instrumentation (Hodgkins et al., 2007). Point precipitation values were averaged over the number of stations within each basin. We compared the point precipitation averages with annual precipitation data from PRISM (Parameter-elevation Regressions on Independent Slopes Model). PRISM is a continuous digital precipitation surface that incorporates topographic information and interpolation to estimate the average basin precipitation. PRISM data sets are recognized to be high quality and are the official climatological data used by some federal US programs (www.prism.oregonstate.edu). A paired t-test indicated 3 of the 23 basins had a significantly different estimate in annual precipitation (p-value <=0.05). The Budyko analysis was performed using both precipitation data sets to ensure robustness of results.

3.4.2 Anthropogenic Contributions: NMS Analysis of Basin Characteristics

Basins throughout the South Atlantic vary in elevation, area, population density, hydrologic infrastructure (reservoir storage and water withdrawals), and land use. We assess the similarities between these types of basin characteristics to describe the relationship of basins with respect to each other's attributes. We then overlayed the estimated human contributions to streamflow changes from the Budyko analyses to see if any patterns emerged. While the Budyko analyses indicate how human activities have changed mean annual streamflow for the period 1970-2005 relative to 1934-1969, most spatial data of basin characteristics exist only for recent years (post-1990). However, these basin characteristics generally change gradually through time and are likely to represent the proportional differences in basin characteristics over the period of 1970-2005. Consequently, we evaluate these relationships qualitatively rather than quantitatively.

Data Acquisition: Anthropogenic Data

We used the National Hydrologic Dataset (NHD) to delineate drainage basins for each USGS stream gauge (http://nhd.usgs.gov/). Land use, water withdrawals, population, and reservoir storage estimates were reflective of conditions at a single point in time (Table 3.2).

Land Cover

The most recent National Land Cover Dataset (NLCD) was available for 2006 at a 30 m resolution (http://seamless.usgs.gov/). NLCD consists of 24 land cover classifications including water, wetlands, development, forest, and agriculture. The NLCD was used to assess the 2006 forest cover, urban development, and agriculture in delineated basins (Figure 3.2D). The NLCD was also used to redistribute county level population and water demand estimates into non-aligning drainage basins (*see below*).

Reservoirs

Reservoir data were obtained from the Army Corp of Engineers National Inventory of Dam database listing major reservoirs only. From this data we calculated the total storage volume based on the year of reservoir completion (Figure 3.4). The average amount of water held by reservoirs was 18% of MAS, with Basin 24 holding a maximum of 124% of MAS.

The Budyko analysis is based on the assumption of constant water storage. This assumption was violated in Basin 15.12 (and any basin with new reservoirs from 1934-2005) as construction on

Falls Lake ended in 1981, adding 42 cm of reservoir storage for the entire basin. We applied the Budyko analysis to basins over time (ΔQ_H) and did not observe a significant change around years of reservoir construction (Figure 3.10). We had anticipated a decrease in streamflow due to increased E and withdrawals. However, our finding of no trend was supported by Degu et al. (2011). They found that a large reservoir constructed in humid subtropical climates exhibits comparable fluxes to the evapotranspiration of a forested land cover at an annual timescale. Thus, the clearing of a forest for reservoir construction is unlikely to create a distinctly different local climate (change in the relationship between E/P, E_p/P of the Budyko curve in Period 1). The sub-humid climate and previous forest cover enabled us to apply the Budyko analysis in basins that had significant changes in storage due to reservoir construction.

Population and Water Demand

County level withdrawal data were obtained from the USGS National Water Use Program (http://water.usgs.gov/watuse/), which has published daily withdrawal data for each category of use every 5 years from 1985 to 2005. Categories of use include public supply, domestic supply, industry, mining, livestock, irrigation, and hydro-electric. We used 2005 withdrawal data for this analysis (non-drought year, unlike 2000 data). We did not include aquaculture or hydro-electric water use since most of the water is non-consumptive (Wachob et al., 2009). We obtained 2005 county level estimates of population from the US Census Bureau (http://factfinder2.census.gov/main.html).

Population and water demand data were available for each county; however, county boundaries do not align with watershed boundaries. The traditional method for estimating basin population assumes population is proportional to the area of overlap with the county. However, population is not uniformly distributed across the landscape. Therefore, we used the NLCD to distribute population within a county for a better spatial estimate of the basin population using the method developed by Patterson and Doyle (2009). See Appendix 3.10.3 for more details. We applied the same distribution method to estimate water demand within a basin. The 2006 NLCD was reclassified into binary rasters representing each category of water demand (Table 3.3).

Non-metric Multidimensional Scaling Analysis of Basin Characteristics

We applied non-metric multi-dimensional scaling (NMS) ordination to summarize the complex relationships between the aforementioned basin attributes, including area and elevation as they impact the magnitude of a streams response to direct human modifications within a basin. We chose NMS over principal component analysis because the basin characteristic variables have different units (population, percent cover, area, etc.) and were non-normal (Table 3.1; McCure and Grace, 2002). While NMS avoids assumptions of normality and linearity, it is sensitive to outliers (McCure and Grace, 2002). We minimized outlier effects by normalizing all variables to their maximum value in our study area. The normalized data were log transformed to reduce the coefficient of variation (CV) below a threshold of 100%, which is the threshold at which skewed data may have a significant impact on results (McCure and Grace, 2002).

A correlation matrix of the transformed variables found population change, number of dams, agricultural demand, and urban water demand to be highly correlated ($r>0.7$) with other variables. For example, the change in population from 1930 to 2005 was correlated with urban water demand ($r=0.99$) and urban land cover ($r=0.93$). After several iterations of NMS, we chose to remove the aforementioned variables from the analysis to reduce the dataset to a smaller number of representative variables (McCure and Grace, 2002). Monte Carlo tests and a broomstick scree plot confirmed the appropriate number of dimensions for this dataset is two. We used the Euclidean distance method for continuous variables (Urban, 2010) and Mantel's test to calculate how much of the variability between basins was captured by the NMS ordination (Urban, 2010).

We overlayed results from the Budyko analysis onto the basins in ordination space in order to observe whether human-induced changes in streamflow (Q_H) were grouped by basin attributes. The Budyko and NMS analysis provided a framework to observe how combined human activities relate to changes in MAS.

NMS accounts for the complex relationship between multiple environmental variables; however it does not provide information regarding how individual variables correlate with the estimated human impact on streamflow. We applied simple linear regressions to assess the impact of discrete variables on Q_H (e.g. total reservoir storage and the $\Delta H\%$).

3.4.3 Spearman Correlation and Mann-Whitney Wilcoxon Rank Sum-test

Climate and streamflow were the only variables with continuous, monthly data. Spearman's rho statistic was used to assess the degree of similarity and strength of association between monthly streamflow and climate (precipitation and temperature). Spearman's rho is appropriate for this analysis because it is a rank order correlation that accounts for non-normality and is robust against outliers (Zhu and Day, 2005; Barringer et al., 1994). We used the non-parametric Mann-Whiney Wilcoxon rank-sum test to determine whether the 50th percentile of mean annual streamflow in AMO (+) phases were significantly different from AMO (-) phase.

Data Acquisition: Atlantic Multi-decadal Oscillation

Atlantic Multi-decadal Oscillation (AMO) monthly SST anomaly values were obtained from the Global Change Master Directory of the National Aeronautics and Space Administration (NASA; http://gcmd.nasa.gov). Our period of record includes an AMO (+) warm phase from 1934 to the mid 1960's and from 1995 to the present. There is an organizational phase of fluctuating SST that lasts for 5 to 10 years between AMO phases (McCabe et al., 2004). The AMO (-) cool phase lasted from 1970 until the early 1990's (Figure 3.2E).

3.5 Results

3.5.1 Establishing Budyko Curves: 1934-1969

Our estimates for average annual E_p in the South Atlantic ranged from 65% to 86% between 1934 and 2005. Our E_p estimates using the Hamon equation were in agreement with Sun et al.'s (2005) estimate of 50% to 80% for the Southeastern U.S.

There was substantial variability in w-parameter values for the study basins, yet limited variability between potential and actual evapotranspiration, indicating similarity in climate but variability in basin characteristics. Values of E_p/P varied from 0.65 to 0.86 in our study area (PRISM estimates ranged from 0.66 to 0.83), whereas the potential evapotranspiration in Australian basins studied by Zhang et al. (2004) had much greater variability (E_p/P ranged from 0.4 to 4.4). In contrast, our w-parameter values ranged from 1.8 (Basin 24.1) to 3.9 (Basin 20), with an average value of 2.6 (Figure 3.5), which was similar to the w-parameter Zhang et al. (2004) found best fit basins characterized by a variety of land cover types (w=2.53). PRISM results had a range in w-parameters from 2.0 to 4.1 (results not shown). Smaller w-parameters are associated with steep slopes, high precipitation intensity that promotes runoff, and lower plant water storage. In contrast, higher w-parameters reflect basins with lower rainfall intensity, low slopes, and high plant water storage capacity (Zhang et al., 2004).

3.5.2 Climate versus Human Drivers: Streamflow Changes in 1970-2005

From Period 1 (1934-1969) to Period 2 (1970-2005), all φ (point E_p/P, E/P) moved left along their respective Budyko curve (Figure 3.6), indicating a regional shift in climate toward decreasing evapotranspiration. Thus, the ΔQ_C was positive since a decrease in E/P translates into an increase in streamflow (Figure 3.3). Psi (φ) had both upward (decreasing ΔQ_H) and downward (increasing ΔQ_H) vertical movement away from the Budyko curve. For example, all φ in Basin 3 moved downward (increase in Q_H), while in Basin 15 all φ moved upward from the Budyko curve (decrease in Q_H). This indicates consistent climatic, but inconsistent anthropogenic contributions to streamflow changes across sites.

The average climate induced increase in streamflow was 3.9 cm (9%; Table 3.4). Twelve basins also experienced an increase in streamflow due to human factors. For these sites the average, additional contribution of Q_H was 2.5 cm (5%), which served to amplify streamflow beyond the increase resulting from climate. In contrast, in ten basins Q_H decreased streamflow by an average of 3.5 cm (-8%) that often mitigated much or all of the increase resulting from climate (Figure 3.7). The relative impact of direct human-induced changes to streamflow exceeded climate in 10 basins.

For HCDN sites, the average absolute human contribution to streamflow was 3% of mean annual streamflow. This was in agreement with our expectation that Q_H in HCDN basins would be less than Q_H in non-HCDN basins (p-value=0.028; Table 3.4).

While all sites showed an increase in streamflow resulting from climate contributions, the largest increases (greater than 15%) in Q_C were observed in the Mountain Region and Coastal Plain (Figure 3.7). The smallest increases in Q_C were located in the Piedmont of NC and SC, and these basins also experienced the greatest human induced decreases in streamflow. Basin 15 and Basin 24 (including sub-basins) were the only basins to have less streamflow in 1970-2005 relative to 1934-1969. In these basins we observe a scenario where anthropogenic impacts leading to streamflow reductions exceeded the increase in streamflow that would have been expected were climate to be the only driver. The results from the Budyko decomposition method did not change significantly when using PRISM precipitation data in place of point precipitation data (see Appendix 3.10.4).

3.5.3 Combined Human Influences on Streamflow: NMS Analysis

In the NMS analysis, axis 1 captured 88.6% and axis 2 captured 10.0% of the variance between basin characteristics (Figure 3.8). The proximity of vectors represents the 'closeness' of the relationship between variables. For example, the total storage vector has a strong negative correlation with agriculture, but a positive relationship with population and percent urban area. Axis 1 is linked most closely with population and agricultural land cover. Axis 2 is linked most closely with percent urban land cover. Total reservoir storage, elevation, and area were linked fairly evenly with both axes. Percent forest was not a strong factor in differentiating basins, which is likely due to the relatively small variation in percent forested values between basins (48%±14%). Components of all vectors are represented on both axes (Table 3.5). The stress value was 0.063, which indicates a good fit of the data.

The combination of selected environmental variables was able to explain some of the variability observed in Q_H based on the NMS analysis (Figure 3.8). Q_H contributed to increased streamflow in large basins and in smaller, high elevation basins. In contrast, Q_H contributed to decreased streamflow in basins with high reservoir storage capacity and large populations. The response of Q_H in agricultural basins was mixed.

3.5.4 Comparing Q_C to Climate Variables and AMO

The Spearman correlation between monthly discharge and precipitation was significant and positive for all basins (Table 3.5). This indicates that precipitation alone could explain 51 to 81% of the observed streamflow changes. In contrast, only two basins had a significant negative correlation between temperature and discharge. In addition, we found 4 (17%) streamflow gauges had a significantly ($p<=0.05$) different median annual streamflow during AMO(+) (mean Q of all basins = 41 cm) and AMO(-) (mean Q of all basins = 45 cm) phase. While most gauges did not have a significant shift in streamflow, the median annual streamflow during the AMO(+) phase tended to be less than the AMO(-) phase. This suggests the AMO does play at least a minor role in long-term streamflow persistence (McCabe et al., 2008).

3.5.5 Comparing Q_H to Basin Characteristics

Total reservoir storage, population density, urban land cover, and urban water demand were negatively related to Q_H; whereas, forest and agricultural land cover were positively related (Figure 3.9). Agricultural water demand did not have a clear relationship. Total reservoir storage had the strongest correlation with Q_H, while water demand and percent forest cover had the weakest correlations.

3.5.6 Temporal shifts in Q_C and Q_H

The further decomposition of Period 2 into 5-yr overlapping time series confirmed that climate and human impacts on watersheds are not stationary (Figure 3.10). All basins had an increase in Q_C% of around 20% in the early 1970's, but many basins also experienced increased streamflow coinciding with a pluvial in the mid 1990's (Figure 3.10). Further, a decrease in Q_C was observed in the early 2000's, which was during a time of regional drought for the South Atlantic. The magnitude of Q_C was smaller in the southern portion of our study area (e.g. Basin 17 and 24; Figure 3.10) and less variable than more northerly basins. Q_C had higher variability over time than Q_H, indicating that on short timescales the greatest management challenges will be changes in the proclivity of flood and drought events. In comparison, monotonic trends in Q_H may present more predictable long-term challenges for water supply.

Q_H did not show consistent temporal patterns across basins. In Basin 2, with high agricultural land cover and low population, Q_H steadily decreased over time. Whereas, in the largely urbanized and high reservoir storage of Basin 15.12, Q_H was negative but remained fairly constant. The smaller head water basins (16.2, 16.21, and 16.11) are highly urbanized and the Q_H for these basins increased in the early 1990's prior to rapidly decreasing (figures not shown). However, in Basin 16, which is much larger and has less proportional development, Q_H steadily decreased (Table 3.1). Basin 24 is located downstream of two large hydro-electric power plants (Wachob et al., 2009) and displayed large fluctuations in Q_H over time, which interestingly, had a positive trend in Q_H during the regional drought from 1999-2002; thereby serving their designed purpose to ameliorating drought conditions.

3.6 Discussion

We decomposed the relative contribution of climate and human factors to changes in mean annual streamflow observed between two time periods for river basins in the South Atlantic and found climate contributed to increased streamflow since the 1970's. In contrast, the human contribution to streamflow varied between basins and either amplified (increased) or masked (decreased) the impact climate had on streamflow. Furthermore, the human induced changes on streamflow were equivalent to, and even exceeded, climate impacts in 43% of the basins.

Observing trends across relatively natural basins often pointed to the importance of exogenous climate controls on streamflow with little attention given to account for variation in endogenous basin properties. However, it is well understood that humans play a major role in controlling how water moves through the landscape, and in human modified basins it has been found that anthropogenic impacts can exceed the effects of climate impacts on streamflow (Arrogoni et al., 2010). In the South Atlantic, when we took into consideration only those natural basins (HCDN sites), we found that Q_H had a smaller impact than $Q_{C.}$; whereas, Q_H exceeded Q_C for 56% of our basins that did not have HCDN status (Table 3.4; Figure 3.7).

3.6.1 Q_C Patterns

We recently demonstrated that streamflow throughout the South Atlantic has been highly non-stationary, characterized by two periods of declining streamflow (1934-1969 and 1970-2005) interrupted by an abrupt increase in streamflow to a wetter climate regime (Patterson et al., Forthcoming; Figure 3.11). The Budyko decomposition method results corroborate these previous findings, indicating climate increased streamflow (mean Q_C = 9±5.6%) during the latter period. These climate related changes were not trivial (range from 0-24% increase in streamflow) and demonstrate that transitions between climate regimes can pose serious changes to streamflow that must be addressed by water resource management.

Within each time period, however, streamflow at many sites declined significantly (Figure 3.11; Patterson et al. (Forthcoming). Since we used the early period to calibrate our Budyko curves, we were only able to assess change in Q_C and Q_H through time during the later period (Figure 3.10). These trends, unlike the shift in streamflow around 1970, did not correspond to consistent changes in Q_C across sites. Interestingly, Q_C tended to have a higher correlation with change in Q over time (Pearson r=0.75±0.12) than Q_H (r=0.58±0.22) due to greater fluctuation in Q_C than Q_H in most basins (Appendix 3.10.5). In contrast, the overall change in Q_H was a better predictor of recent trends in streamflow (r=0.8) compared to Q_C (r=0.54).

3.6.2 Q_H patterns

The human impact on streamflow between the two time periods (Q_H range=-18% to 12%) either masked or amplified the increase associated with Q_c. Basins with large reservoir storage and high populations were linked to the largest human-induced decreases in streamflow. In contrast, the basins geographic properties, such as elevation and area, provide information regarding the level of impact a change in human factors will likely have on streamflow (Figure 3.8). High elevation basins tend to have smaller area, while low elevation basins tend to be larger and large watersheds tend to reduce the variability in streamflow due to the composite of diverse human impacts. The ability for humans to significantly alter streamflow increases as basin size decreases because smaller basins tend to have distinctive characteristics (e.g. a dominant land type or activity) and are therefore more sensitive to anthropogenic impacts (Trimble and Weirich, 1987).

There were some generalizations between anthropogenic characteristics and the direction and magnitude of human induced changes in streamflow. Total reservoir storage had the strongest relationship with Q_H and was negatively related (R^2=0.29; Figure 3.9). Population density (R^2=0.16), percent urban land cover (R^2=0.10), and urban water demand (R^2=0.05) were all negatively related to Q_H. Both reservoir and urban correlations were in agreement with NMS results (Figure 3.8B) and we hypothesize that increasing population is likely to result in an overall decrease in streamflow due to a combination of increased water demand and greater reservoir storage.

The negative relationship of Q_H to reservoir storage agreed with findings from Wang and Hejazi (2011). Large reservoirs in the South Atlantic often serve multiple purposes such as flood control, water supply, recreation, and hydropower. Trimble and Weirich (1987) hypothesized that reductions in streamflow for the Piedmont would become significant as increasing amounts of water are needed to meet urban and agricultural water demands.

Percent agriculture land cover was positively related to human induced changes in MAS (R^2=0.17). This relationship may indicate that the concentrated increase in E/P (decrease in streamflow) during the summer is more than offset by the reduced E/P (increase in streamflow) when fields are fallow (Shilling et al., 2008). Agricultural water demand had a slight, positive relationship to Q_H. The weak link is not surprising given that irrigation in the South Atlantic represents a small percentage of total agricultural farmland (there were 150,000 acres of farm land irrigated in 2008 out of almost 9 million total acres of farmland in North Carolina) and irrigation is largely used to supplement rainfall volumes (withdraw an average of 20 days per month; NCAGR, 2011).

We found the opposite trend from Wang and Hejazi (2011) with respect to population density and percent urban land cover. This is not unreasonable since their highest urban land cover was less than 4% of the watershed. In contrast, our basins had up to 30% impervious land cover. Arrigoni et al. (2010) were unable to find a clear relationship between streamflow and urbanization. Perhaps the difficulty in finding a clear relationship reflects Dunne and Leopold's (1978) observation that urbanization simultaneously increases peak runoff and decreases low flows due to reduced groundwater recharge. Thus, streams become more responsive to rainfall events, but at an annual scale streamflow may decrease. These impacts become increasingly noticeable after the watershed exceeds a threshold of 10% impervious surface (Arnold and Gibbons, 1996). Additionally, urbanization is tied to an increased demand on water resources, which further decreases streamflow (Claessens et al., 2006).

Forests are recognized as playing a significant role in regulating water resources in the South Atlantic (Sun et al., 2005). Sun et al. (2005) predicted that deforestation in the South Atlantic would result in greater streamflow because less water would be lost to Ep. However, we do not have the data to link changes in forest cover to streamflow. Instead, we found no relationship between current forest cover and average Q_H over a 35 year period.

3.7 Policy Implications

The majority of regional studies focused on streamflow changes only consider relatively unmodified basins in order to attribute changes in streamflow to climate due to the difficulty of pulling apart climate and human impacts on streamflow (e.g. Lettenmaier et al., 1994). However, streams that serve as water supply are typically located in basins where streamflow is altered by human activities and it is useful to be able to differentiate between climate and human impacts on streamflow in order to inform decision-making.

3.7.1 Policy Implications: Climate

The most predictable component of climate change is thought to be associated with human activities that increase greenhouse gases, which increase temperature and E_p (Huntington, 2006). In our study area, we found that P increased faster that T and resulted in a decrease in the ratio of E/P; thereby, resulting in climate contributing to an increase in streamflow. It is uncertain whether the abrupt increase in precipitation and streamflow around 1970 is the result of an oscillation in SST's (Figure 3.2E; Tootle et al., 2005), a faster water cycle due to increasing global temperatures (Trenberth, 2011), or an amplifying impact of both of these conditions. One challenge is predicting when abrupt changes in climate regimes will occur and how those changes will interact with monotonic increases in temperature to overall impact streamflow conditions (e.g. McCabe et al., 2008; Enfield et al., 2001). Despite our current inabilities to accurately predict a reversal in climate regimes, there is a need to develop policies in the advent that this region returns to a drier hydrologic state.

3.7.2 Policy Implications: Human

Reservoir storage in the South Atlantic is not likely to change significantly in coming years as suitable sites for large reservoirs are currently in use (Figure 3.3). However, we do anticipate population, and therefore urban growth and water demand to increase over time in many of these basins (Figure 3.2A). Water demand is less certain as water efficient technologies increase and water demand strategies become more prominent. Thus, water demand may increase at a slower rate than population (Franczyk and Chang, 2008). In addition, changes in land use that occur as pasture and forest are converted to urban landscapes will impact water resources (Figure 3.2C). The management of a certain landcover type can have significant influences on streamflow (e.g. forest management strategies, green infrastructure, and irrigation practices; Nisbet, 2005; Trimble and Weirich, 1987). Unlike climate, endogenous controls are potentially easier to address (particularly in upstream basins) because they are constrained to the basin scale and can be directly influenced through management practices. The direct-human induced impact on streamflow is great enough that future water management scenarios should use recently available streamflow records as the starting point for planning rather than relying on long-term historic streamflow records that may be predominantly climate driven.

3.8 Tables

Table 3.1: Physical and hydrological characteristics of watersheds. Blue text = HCDN basins (no major human modifications of landscape).

					Climate		*Development*			*Agriculture*		*Forest*	*Reservoirs*	
Basin ID	Gauge	Elev (m)	Area (km^2)	2005 Q (CM/YR)	2005 PCP (CM/YR)	Mean 2005 Temp (C)	Pop (thous.) 2005	2005 Water Demand (CM/YR)	% Urban 2006	2005 Water Demand (CM/YR)	% AG 2006	% Forest 2006	# Dams	Total Storage (CM)
1	1644000	83	860	54.6	82.3	26.3	46.7	0.34	7%	0.14	53%	40%	2	0.5
2	1634000	162	1994	30.2	81.0	29.7	59.4	0.73	7%	0.23	35%	58%	6	0.6
3.1	1625000	329	966	33.1	89.9	30.9	56.7	2.29	14%	0.22	48%	38%	0	0.0
3.2	1622000	344	974	42.8	74.8	29.1	66.2	3.60	9%	0.27	31%	60%	9	4.8
3	1628500	332	2795	39.2	82.3	30.0	173.6	2.42	12%	0.25	38%	50%	17	2.0
5	2035000	49	16193	46.6	108.1	30.2	432.7	0.52	6%	0.05	15%	75%	38	6.1
11	2077000	102	1417	36.0	101.6	30.6	32.1	0.52	6%	0.14	26%	57%	2	0.8
12	2080500	15	21714	38.3	93.4	32.2	480.0	0.44	6%	0.09	19%	64%	25	24.9
15.12	2087500	54	2978	29.2	96.1	33.7	718.2	4.01	25%	0.30	15%	49%	7	45.6
15.1	2089000	22	6213	32.9	97.7	33.2	1092.1	2.83	18%	0.50	25%	36%	7	21.8
15	2089500	6	6972	35.4	101.1	33.5	1158.0	2.70	18%	0.54	28%	34%	7	19.5
16.11	2100500	133	904	32.8	100.7	33.7	203.6	3.47	29%	0.57	25%	40%	2	4.9
16.1	2102000	57	3714	33.1	100.7	33.7	316.7	1.40	12%	0.56	21%	56%	5	1.5
16.21	2094500	194	339	17.4	85.5	33.1	85.6	4.18	30%	0.23	21%	40%	3	21.5
16.2	2096500	160	1570	36.6	85.5	33.1	303.7	3.47	25%	0.55	25%	40%	5	9.1
16	2102500	37	8972	31.1	97.7	33.3	1076.,1	2.10	13%	0.48	21%	55%	19	25.5
17.1	2126000	77	3553	34.2	114.3	33.5	488.3	2.31	18%	0.57	33%	42%	3	1.2
17.2	2116500	196	5905	58.7	113.2	30.7	509.6	1.69	13%	0.42	22%	59%	8	6.9
17	2129000	38	17775	45.3	110.3	32.8	1525.6	1.45	13%	0.43	25%	54%	23	7.6
20	2136000	12	3243	24.8	107.8	35.0	133.0	0.97	8%	0.22	35%	17%	0	0.0
21	2148000	41	13131	48.9	174.4	33.2	1527.3	2.59	19%	0.10	13%	58%	42	27.4
24.1	2167000	113	3522	63.4	120.0	34.2	366.9	2.38	15%	0.04	15%	56%	13	33.2
24	2169000	53	6527	45.2	124.1	34.2	546.7	1.87	14%	0.08	16%	54%	14	59.7

Table 3.2: Data sources and their temporal and spatial extent of coverage.

Data	Source	Frequency	Temporal Extent	Spatial Extent
Stream flow	USGS	Monthly	1934 to 2005	Point
Climatic Data				
Precipitation	Southeast Regional Climate Center	Monthly	1934 to 2005	Point
Temperature	Southeast Regional Climate Center	Monthly	1934 to 2005	Point
Anthropogenic Data				
National Land Cover Data	USGS	N/A	2006	30 m resolution
Population	Census	Decade	2005 estimate	County
Water Use	USGS	5 years	2005	County
Reservoirs	National Atlas	N/A	Varies	Point

Table 3.3: Water demand linked to NLCD categories.

Water Demand (Freshwater)	NLCD Category	NLCD Value
Public Supply*, Domestic Self Supplied, Industrial Self Supplied	Developed – Open through High Intensity	21, 22, 23, 24
Irrigation Self Supplied, Livestock Self Supplied	Cultivated Crops, Pasture/Hay	81, 82
Mining – Self Supplied	Barren	31

* Public Supply includes water used for domestic, commercial, industrial, and outdoor watering. Self-supplied indicates a separate water source from public supply.

Table 3.4: Climate- and human- induced changes to streamflow by basin.

Basin ID	Gauge	HCDN	Q_H (cm)	Q_c (cm)	%Q_H change	%Q_c Change	Total % Q Change
1	1644000	No	4.68	6.86	12%	17%	28%
2	1634000	No	-1.17	8.08	-3%	24%	20%
3	1628500	No	2.22	5.89	5%	14%	20%
3.1	1625000	No	0.38	3.80	1%	10%	11%
3.2	1622000	No	5.29	1.98	12%	4%	16%
5	2035000	Yes	1.90	5.43	4%	11%	15%
11	2077000	No	-3.97	6.22	-9%	15%	5%
12	2080500	No	1.72	2.36	4%	5%	9%
15	2089500	No	-5.12	4.03	-10%	8%	-2%
15.1	2089000	No	-5.24	4.04	-11%	8%	-2%
15.12	2087500	No	-8.69	5.53	-18%	12%	-7%
16	2102500	No	-2.24	3.60	-5%	8%	3%
16.1	2102000	Yes	-1.25	1.73	-3%	4%	1%
16.11	2100500	No	3.02	1.61	7%	4%	10%
16.2	2096500	No	3.88	3.18	9%	7%	16%
16.21	2094500	No	-3.50	3.20	-10%	9%	-1%
17	2129000	No	2.82	2.38	6%	5%	10%
17.1	2126000	Yes	-1.13	6.16	-3%	14%	12%
17.2	2116500	Yes	1.93	2.85	3%	5%	8%
20	2136000	Yes	0.66	5.31	2%	16%	18%
21	2148000	No	0.89	2.23	2%	4%	6%
24	2169000	No	-3.31	2.33	-6%	5%	-2%
24.1	2167000	No	-3.10	-0.14	-5%	0%	-5%

Table 3.5: NMS axes and monthly spearman correlation results by basin. Blue text = HCDN basins.

	NMS Results		Spearman Correlation Results		Wilcoxon Results
Basin	Axis 1	Axis 2	Precipitation to Streamflow Rho	Temperature to Streamflow Rho	Streamflow p-value
1	-1.23	-0.26	**0.65**	**-0.28**	0.41
2	-1.01	-0.11	**0.70**	-0.12	0.50
3.1	-1.44	0.08	**0.76**	**-0.34**	0.07
3.2	-0.77	0.49	**0.78**	-0.07	0.56
3	-0.63	0.12	**0.81**	-0.11	0.18
5	0.38	-0.52	**0.56**	0.12	0.08
11	-1.06	-0.18	**0.56**	0.12	0.82
12	0.99	-0.50	**0.63**	-0.05	0.14
15.12	0.75	0.48	**0.60**	0.04	0.17
15.1	0.86	-0.04	**0.66**	0.02	0.53
15	1.19	-0.25	**0.65**	0.01	0.46
16.11	-0.34	0.43	**0.64**	0.03	0.15
16.1	-0.25	-0.29	**0.61**	-0.01	0.81
16.21	-0.32	1.06	**0.64**	0.06	0.99
16.2	-0.11	0.40	**0.67**	0.05	0.35
16	0.84	0.01	**0.65**	0.05	0.70
17.1	-0.28	-0.32	**0.66**	-0.01	**0.05**
17.2	0.12	0.06	**0.51**	0.05	0.08
17	0.71	-0.46	**0.63**	0.03	**0.02**
20	-0.72	-1.04	**0.63**	0.05	**0.03**
21	1.02	0.04	**0.60**	0.03	**0.00**
24.1	0.45	0.44	**0.58**	-0.07	0.19
24	0.85	0.35	**0.61**	-0.00	0.40
Mantel's R	**0.89**	**0.10**	0.64±0.07	-0.02±0.11	

*P-value <= 0.05 are in bold

3.9 Figures

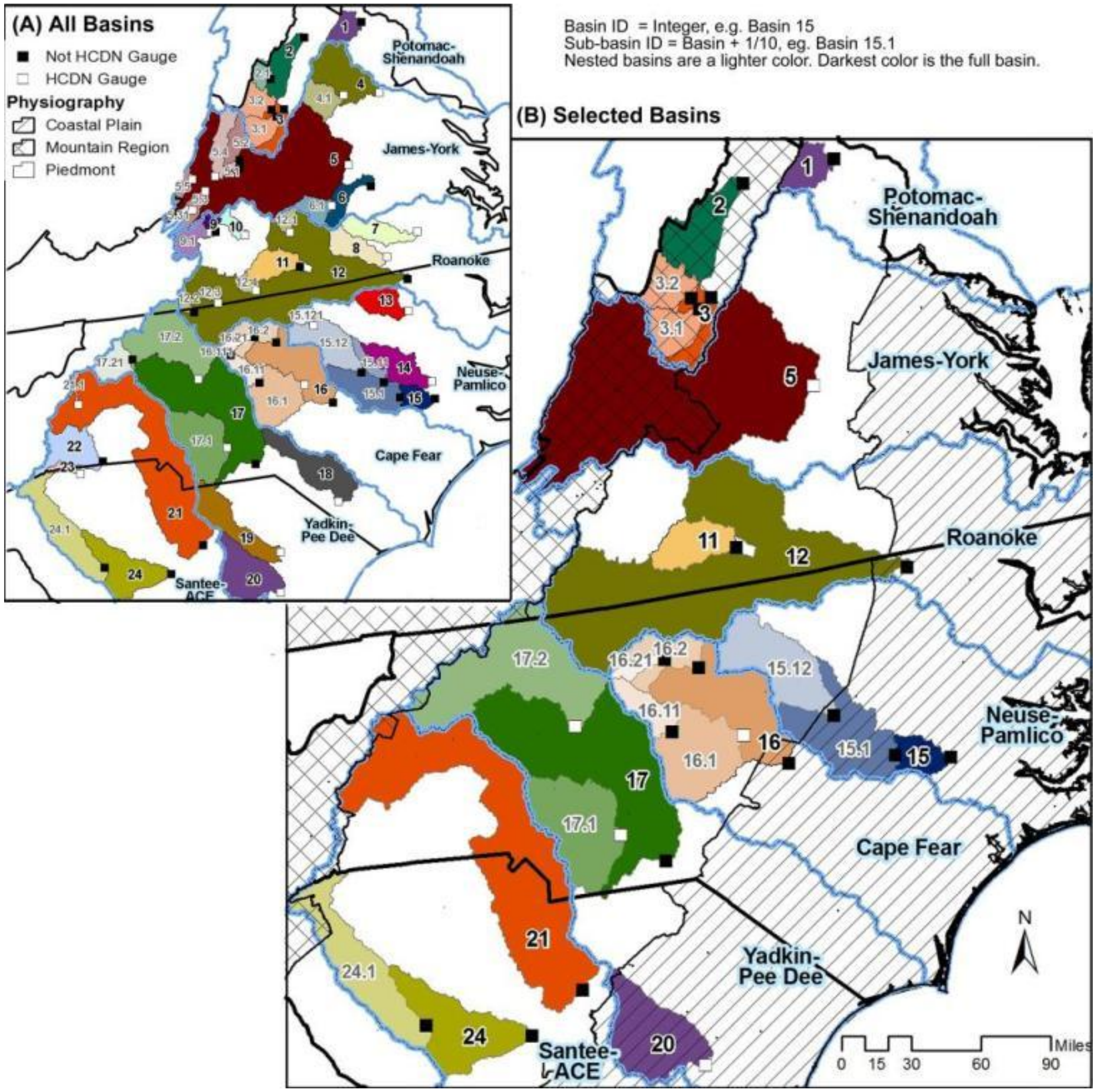


Figure 3.1: Basins corresponding to USGS gauges located in the South Atlantic. (A) All gauges for streamflow trend analysis (n=54). (B) Subset of gauges that included both temperature and precipitation data for the entire record (n=23).

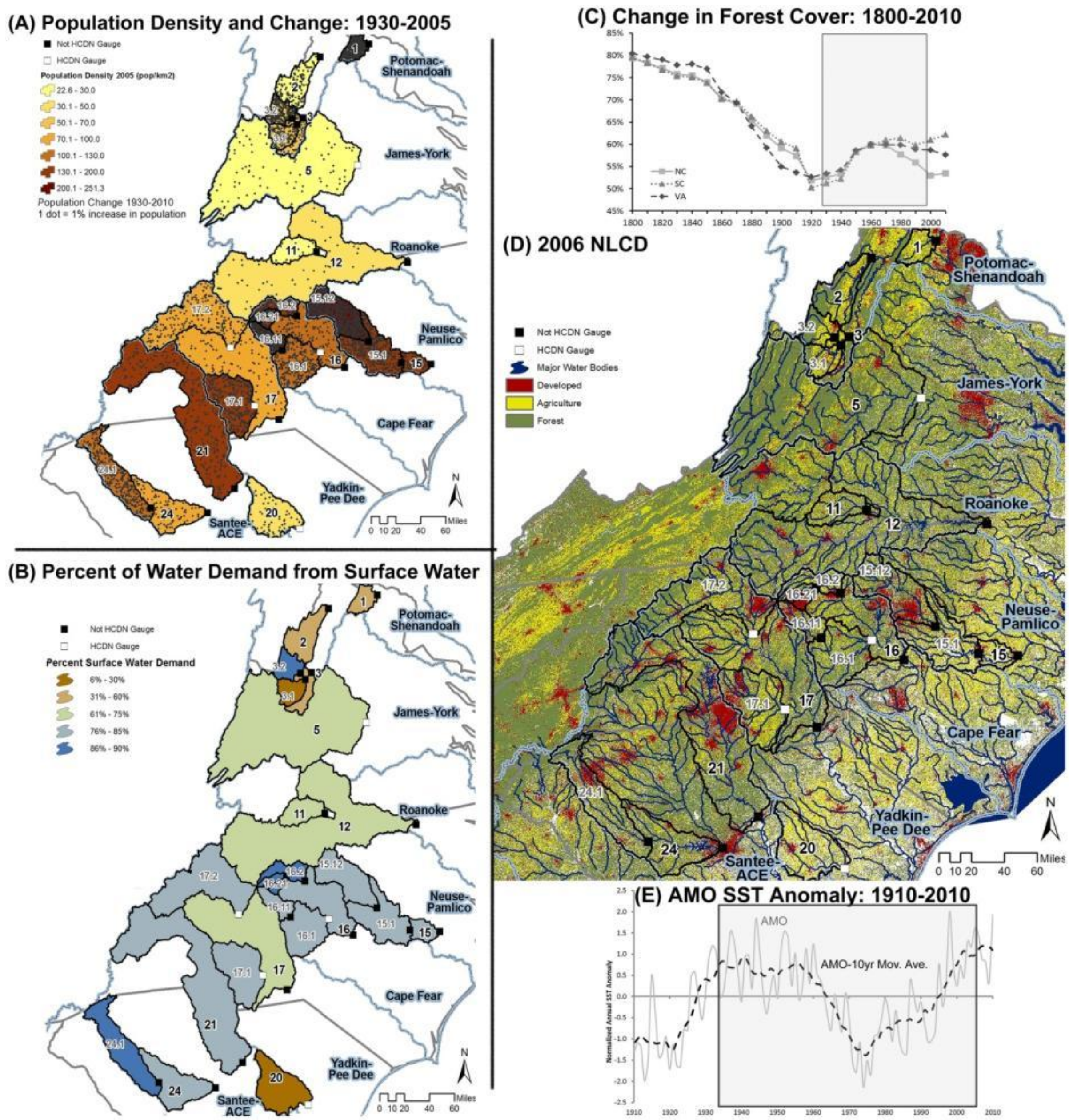


Figure 3.2: Basin characteristics. (A) Population density and change relative to 1930. (B) Percent total water demand met through surface water supplies. (C) Change in percent forest cover for the state over time; window highlights time period of analysis. (D) Urban, agricultural, and forested land cover in 2006. (E) AMO phase through time; window highlights time period of analysis. See Appendix 3.10.2 for data source information.

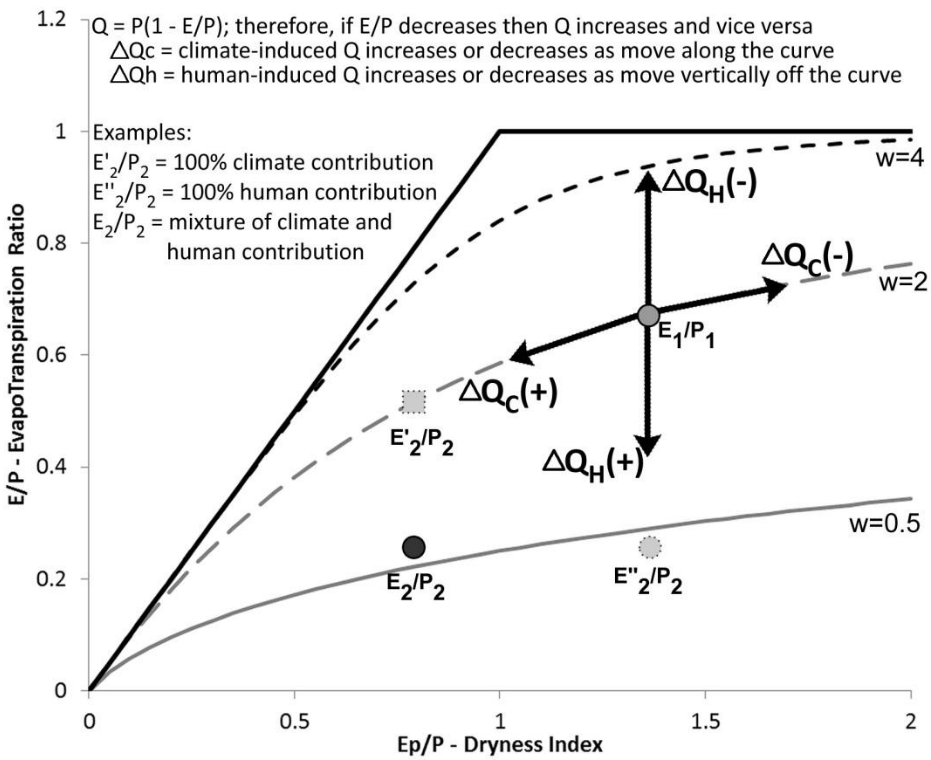


Figure 3.3: Budyko curve displaying the climate and direct human impact of change in E/P on streamflow. $E_{1/}P_1$ (E_2/P_2) is the coordinate during Period 1: 1934-1969 (Period 2: 1970-2005). Climate -induced changes in streamflow move along the original Budyko curve (e.g. E_2'/P_2). Human-induced changes in streamflow move vertical to the original Budyko curve (e.g. E''_2/P_2). E_2/P_2 includes both climate and human-induced changes. Three Budyko curves were plotted with different w parameters ranging from w=4 (forested, favors E/P) to w=0.5 (urbanized, does not favor E/P).

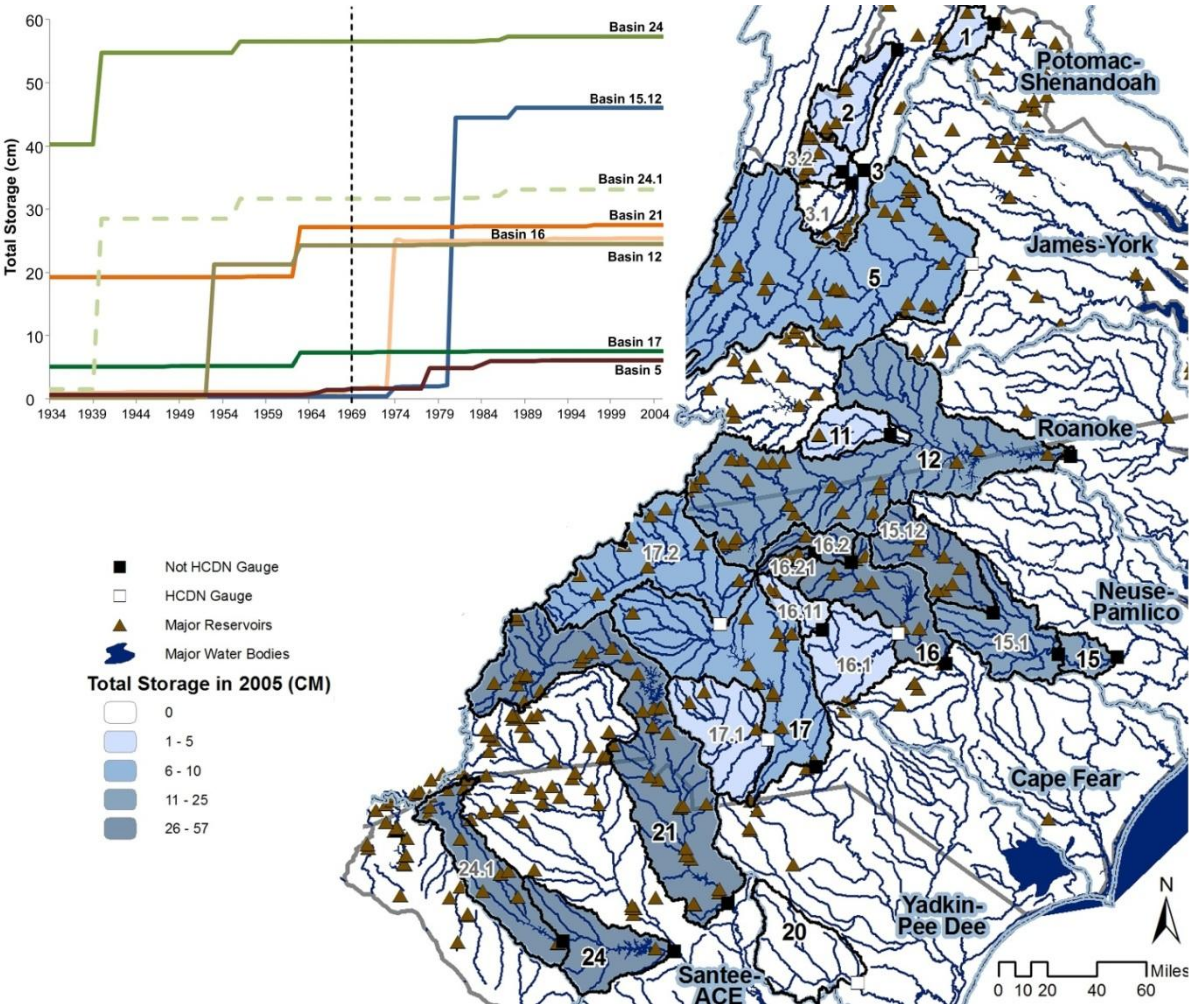


Figure 3.4: Major reservoirs with total reservoir storage per basin as of 2005 displayed on the map. The chart highlights the cumulative reservoir storage for selected basins through time. The dotted line shows the division of the entire record into two sub-periods for the analysis.

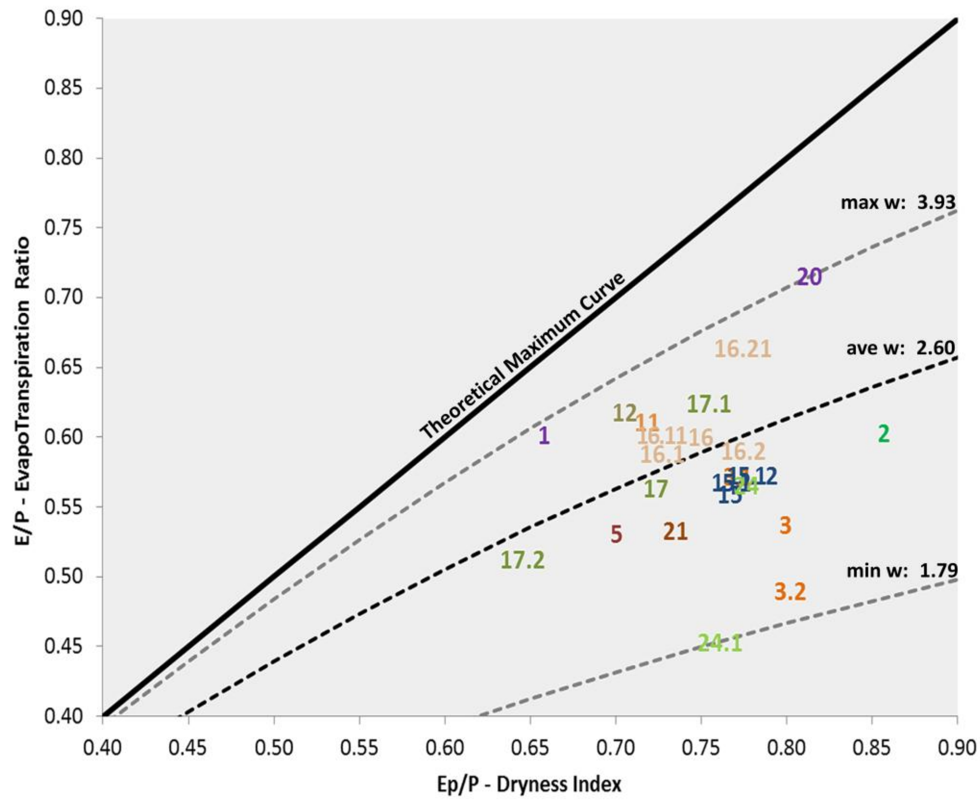


Figure 3.5: Initial starting points (E_p/P, E/P) for all basins during Period 1 (1934-1969). Black line represents the theoretical boundary where E_p=P. Minimum, average, and maximum w-parameters in our study area are shown. Numbers and colors correlate to Basin ID in Figure 3.1.

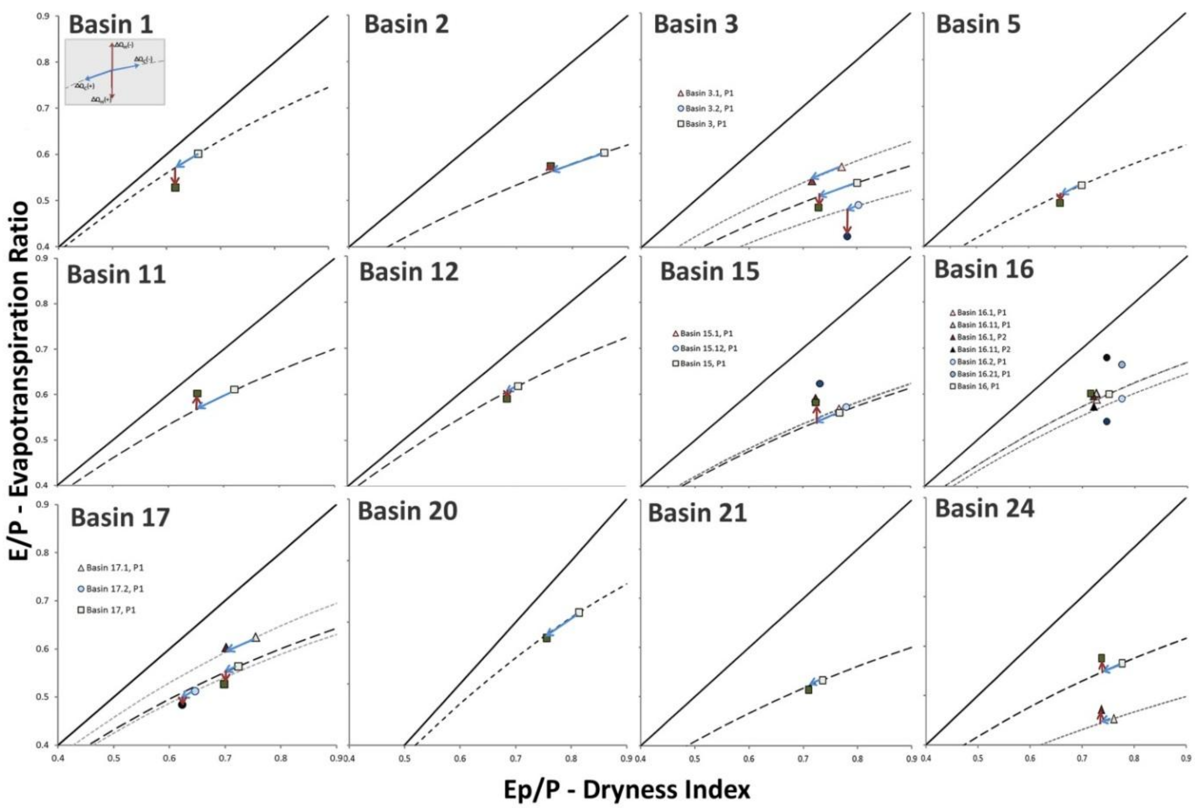


Figure 3.6: Change in φ for each basin from Period 1 (1934-1969) to Period 2 (1970-2005). The Budyko curve based on the w-parameter for Period 1 is shown. Blue arrows represent movement along the Budyko curve (climate component) and red arrows represent the vertical human component away from the initial Budyko curve. Arrows are shown for representative basins in Basin 15 and 16 to avoid cluttering. Basin 5, 16.1, 17.1, 17.2, and 20 were HCDN designated.

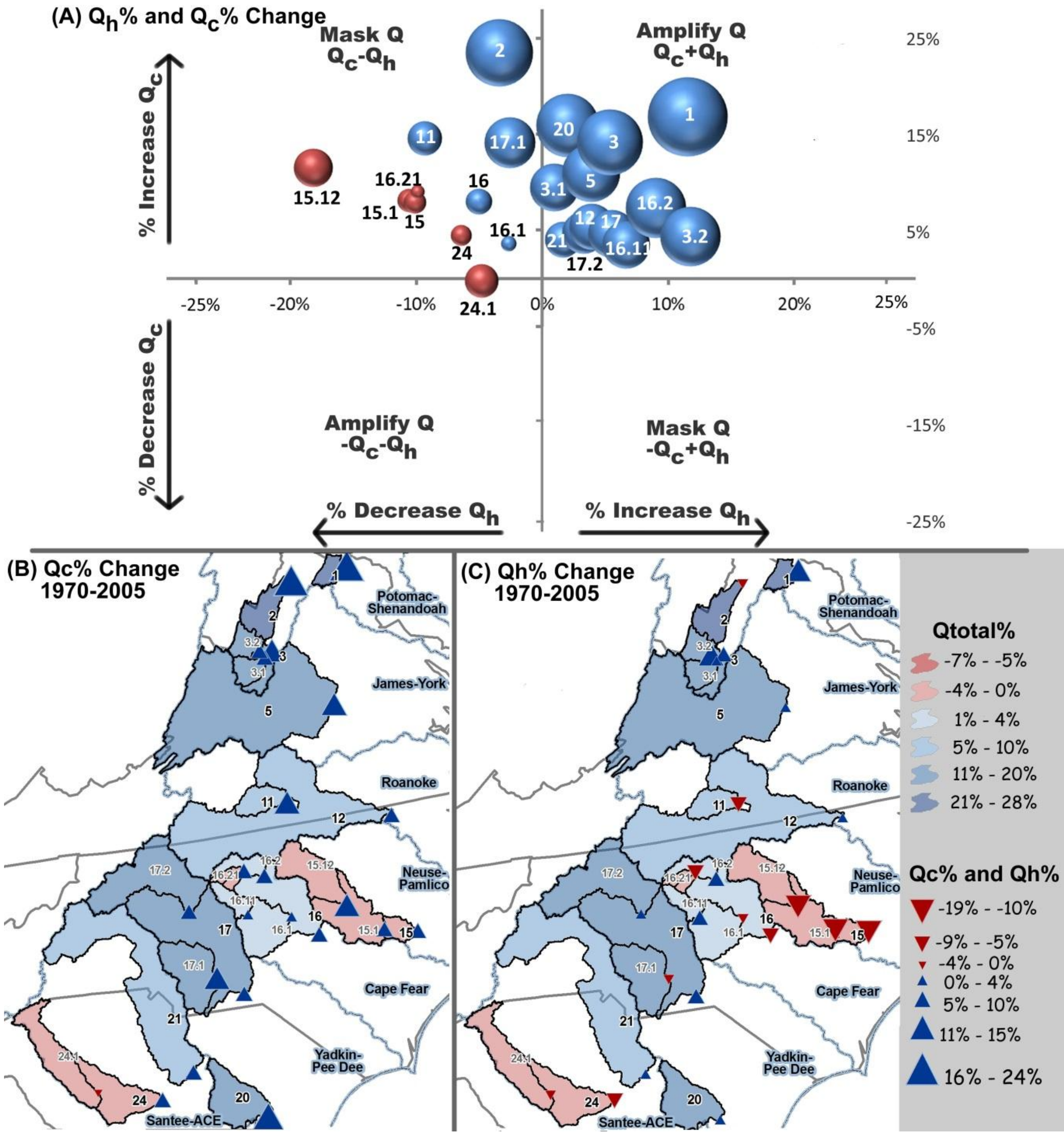


Figure 3.7: (A) Contribution of both climate and human impacts on the total change in streamflow. Bubble size represents total change in Q. Blue (red) is an increase (decrease) in observed streamflow. (B-C) Basin shade is the total percent change in streamflow relative to 1934-1969. (B) Percent change by climate. (C) Percent change by human factors.

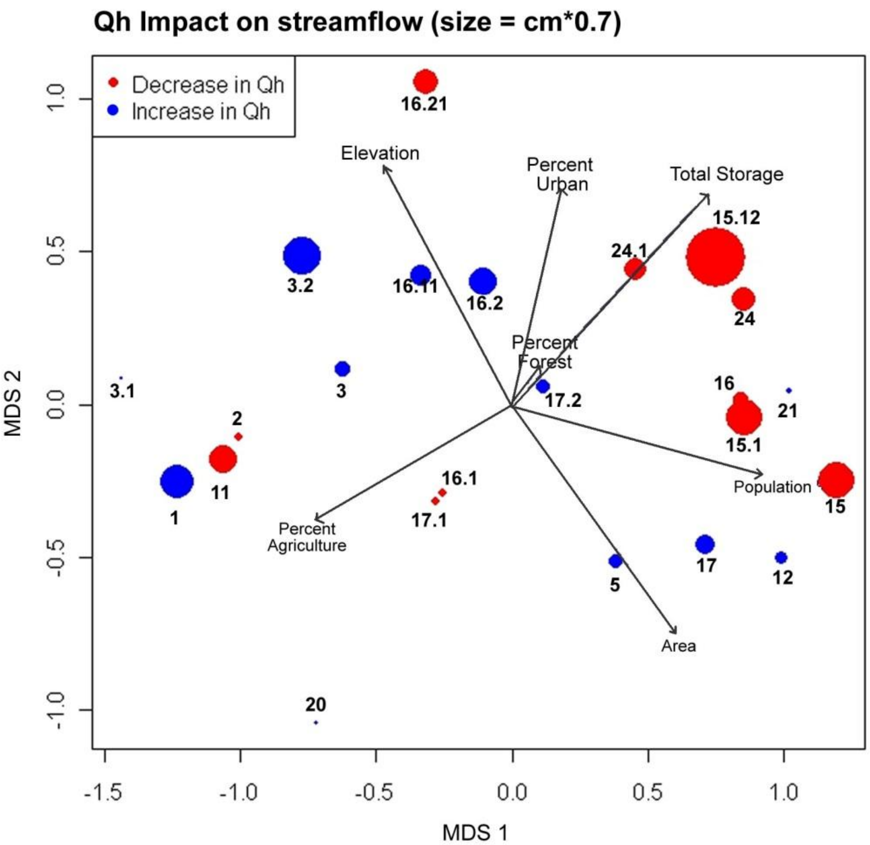


Figure 3.8: NMS representation of basins in ordination space showing similarities between basins based on selected characteristics (vectors). Human induced changes on streamflow (Q_H) are overlayed observe if Q_H clustered with basin's sharing similar characteristics. Axes 1 and 2 explained 88% and 10% of the total variation, respectively.

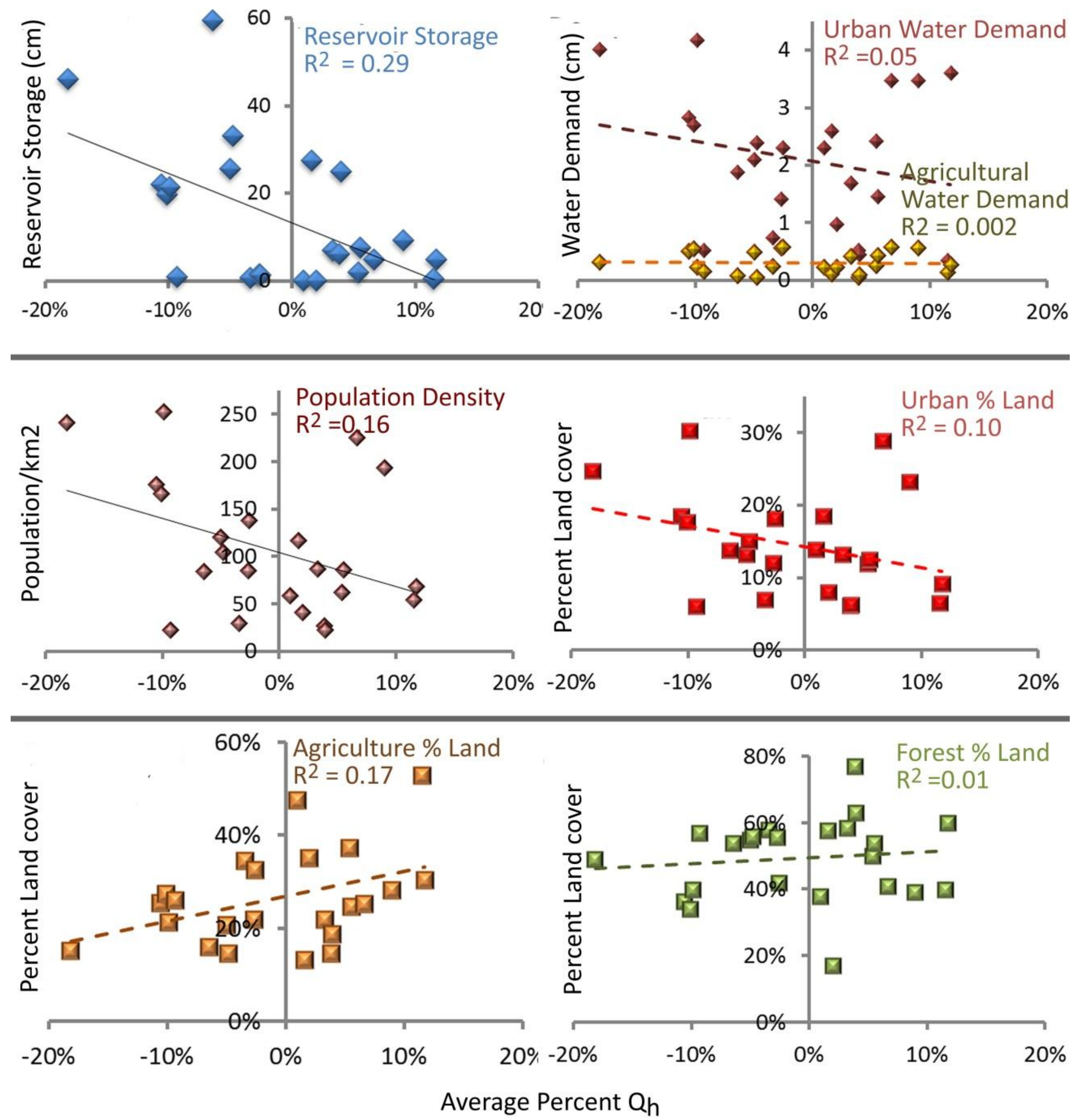


Figure 3.9: Comparison between Q_H% and environmental variables in the NMS and R^2 value. Correlations shown from top left to bottom right are: reservoir storage, water demand, population density, as well as percent urban, agriculture, and forest land cover.

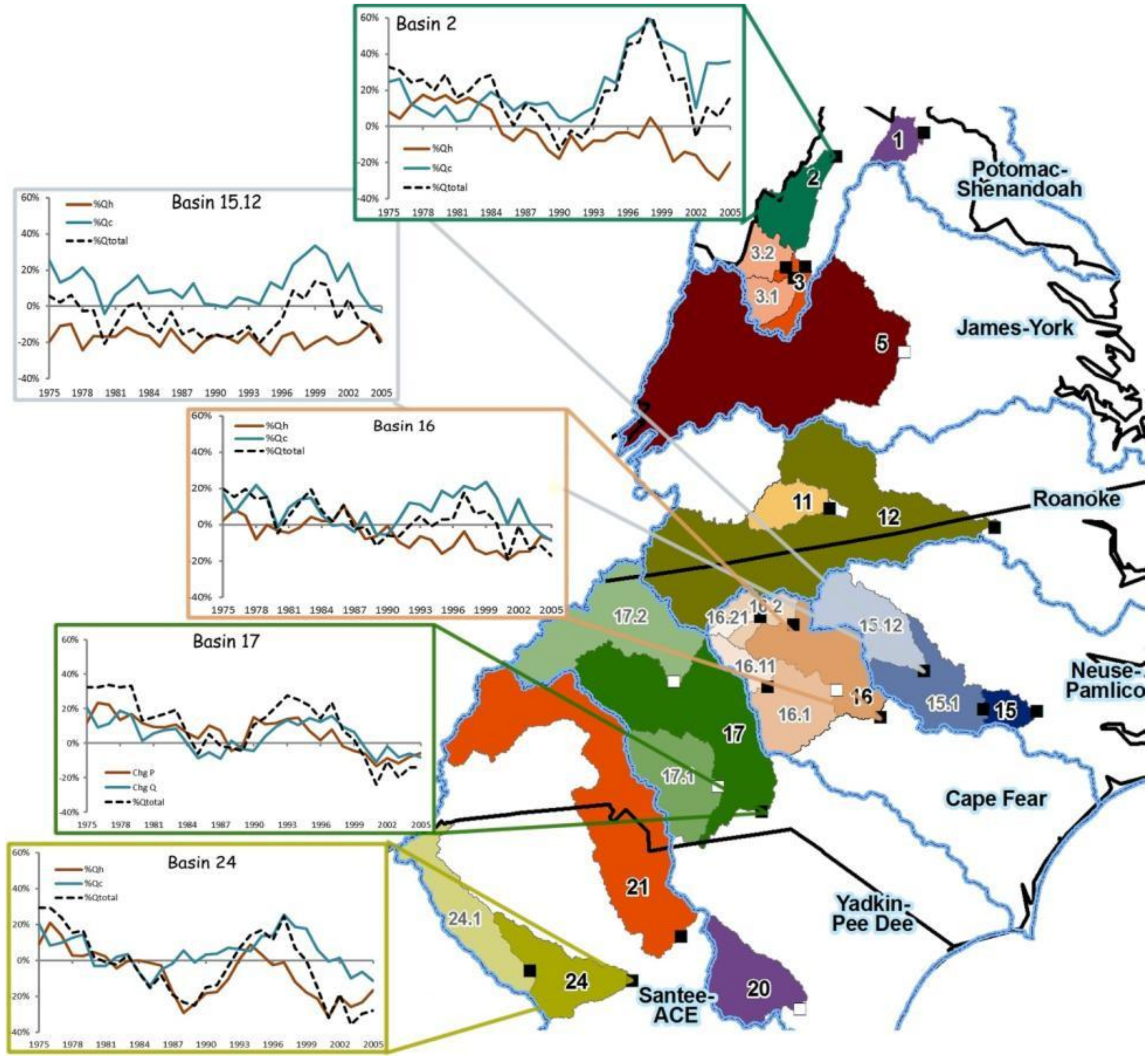


Figure 3.10: Temporal changes in Q_H and Q_C for selected basins. Curves are calculated in a 5 year average moving window to show the variation in Q_C and Q_H over time. Due to space constraints, only a few basins are shown.

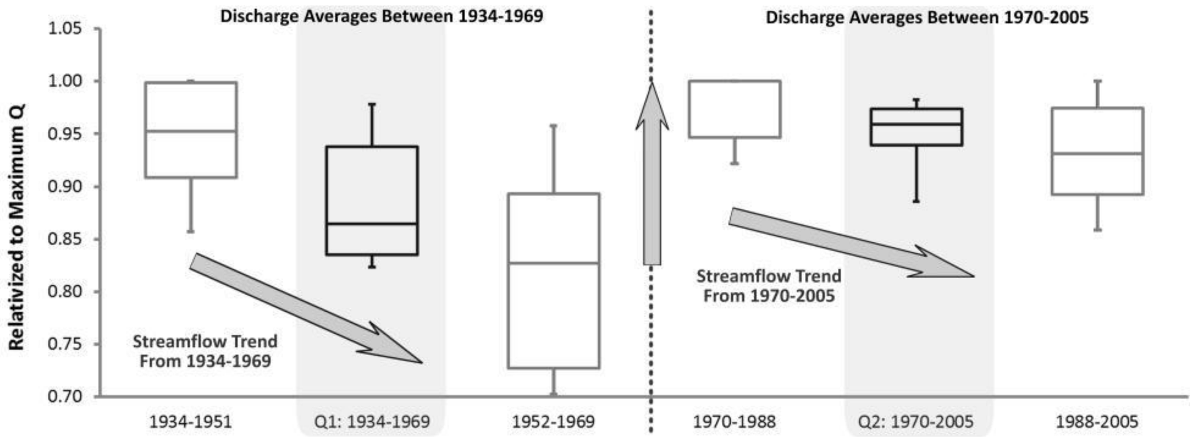


Figure 3.11: Normalized discharge for all basins to the maximum Q for each basin. Boxplots represent the 10th, 25th, 50th, 75th, and 90th percentiles. The shaded boxes represent the two time periods used in the Budyko analysis. Each time period is divided into two halves to show the general streamflow trend within that time period. An SMK trend test confirmed an increase in streamflow for 48 sites from 1952 to 1988 (22 had a p-value <= 0.05).

3.10 Appendix

3.10.1 Hamon Equation for Calculating Evapotranspiration

Equations for calculating E_p using the Hamon method were derived from Xu and Singh (2001) and Forsythe et al. (1995).

1. Hamon Method for calculating monthly (E_p): 1.397*Wt*d*D^2, where
   a. $W_t = \frac{4.95*\exp(0.062*Temp)}{100}$, where Wt is the saturated water vapor density
   b. D = the daylength
      i. Based time of year (in degrees): $\theta = 0.2163108 + 2 * tan^{-1} * \left[0.9671396 * \tan\left(0.00860 * (J - 186)\right)\right]$, where J = Julian day of year (we used the 15th day of the month)
      ii. Transform p to radians: $\phi = sin^{-1} * (0.39795 cos\theta)$,
      iii. Add location: day length, $D = 24 - \frac{24}{\pi} cos^{-1}[\frac{sin\frac{p\pi}{180} + sin\frac{L\pi}{180} sin\emptyset}{cos\frac{L\pi}{180} cos\emptyset}]$, where L = Latitude in decimal degrees and p = coefficient describing definition of daylength (sunrise to sundown).
   c. d is the number of days in a month, and 1.397 is the coefficient used for the South Atlantic. These two modifiers results in units of cm/month (original coefficient for inches/day = 0.55).
2. The average monthly E_p was totaled to obtain the average annual E_p for each basin.

3.10.2 Population and Forest Data Sources

We obtained decadal, county level population data from 1930 to 2000 from the National Historic Geographic Information System (NHGIS) program through the University of Minnesota Population Center (http://www.nhgis.org/). This information was used to calculate the change in basin population over time (Figure 3.2A). Water demand has become more decoupled from population as the per capita water use in the United States began decreasing in the 1980's (Franczyk and Chang, 2009; Gleick, 2003). We found that between 2000 and 2005 the average water demand decreased by 4.3%, despite an average increase in population of 18% and drought conditions in 2000 (often associated with increased demand).

The Forest Inventory and Assessment (FIA) is a national program responsible for maintaining a census of our nation's forest. Statewide, decadal estimates of forest cover were obtained from FIA between 1880 and 2007 (http://www.fia.fs.fed.us/). Historic county or watershed forest estimates are not available. This data provides a general historic context for forestry trends in the South Atlantic (Figure 3.2C).

3.10.3 Method for Distributing Population and Water Demand within a Basin

Briefly, we assigned each land cover type a weighting factor in order to (1) attract population to developed pixels (e.g. residential) and (2) limit the population located in undeveloped pixels (e.g. wetlands). Weighting factors were based on values used by Oak Ridge National Laboratory's LandScan USA model (Bhaduri et al., 2007). The weighted NLCD ($NLCD_{Weight}$) was divided by the sum of all $NLCD_{Weight}$ pixels located within the county to determine the percent population assigned to each pixel (Equation 3.5). The population was then summed for each basin. See Patterson and Doyle (2009) for a more detailed description of the method and its accuracy.

Equation 3.5

$$Population_{Basin} = \sum_{Basin} \left(\frac{Population_{County} \times NLCD_{Weight}}{\sum_{County} NLCD_{Weight}} \right)$$

Water demand was converted from Mgal/day to cm^3/yr. Water demand for each category in the county was divided by the number of pixels within that county to get cm/pixel for each water demand category ($WatDemand_{SW,GW\ Category}$). $WatDemand_{SW,GW\ Category}$ was multiplied by the respective binary $NLCD_{Category}$ raster to determine the spatial distribution of water demand. Total surface and groundwater demand for each basin was summed by category (Equation 3.6) and divided by basin area to get the volume of water (cm).

Equation 3.6

$$WaterDemand_{Basin} = \sum_{Basin} \sum_{SW,GW\ Category} \left(\frac{WatDemand_{SW,GW\ Category} \times NLCD_{Category}}{\sum_{County} NLCD_{Category}} \right)$$

3.10.4 Budyko Analysis with PRISM data

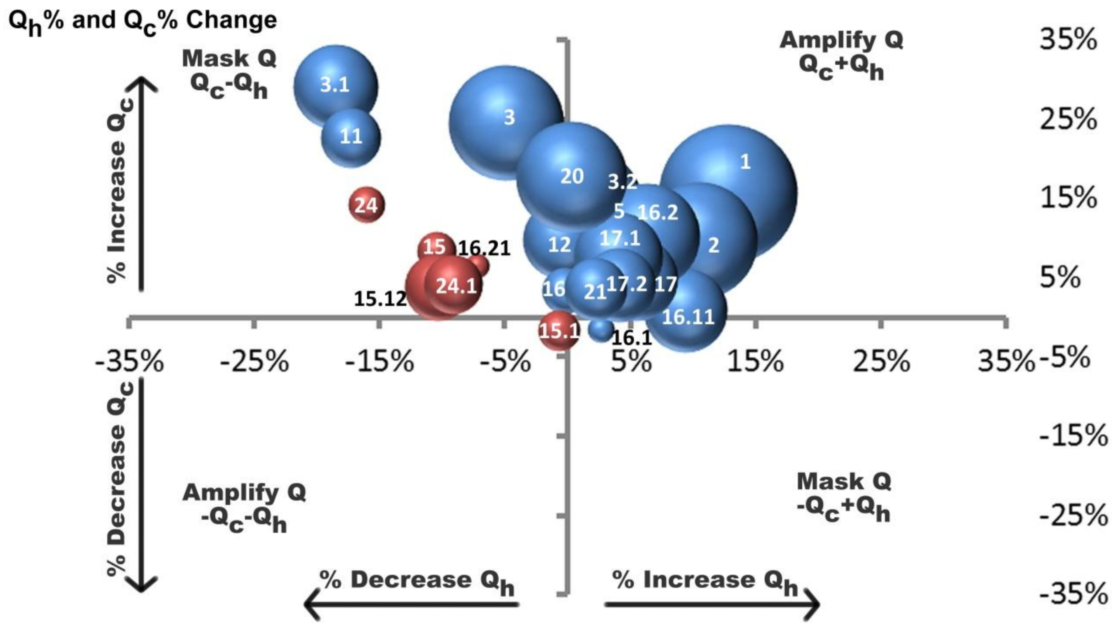


Figure 3.12: Qh and QC results using PRISM data instead of point precipitation data. There was not a significant difference in results (Q_C and Q_H p-val = 0.65).

Paired t-tests between point and PRISM data indicated 3 out of the 23 basins had a significant difference in precipitation values (p<=0.05). The average difference in precipitation for each basin over the 80 year period was ~0% with an average range of values ±17% annually. The tendency was to shift the φ_1 values toward a more energy-limited environment. The average difference between Q_H and Q_C was ±0.7%, with the greatest variation observed in the mountainous basins (10 to 20% deviation). Basin at 15.1 and 24 were the only other basin with a difference of 10% between point precipitation and PRISM precipitation estimates in Q_H and Q_C.

3.10.5 Effect of Nested Basins: Subtraction Analysis

There are several nested basins within our study area that provided an opportunity to estimate the direct anthropogenic impact on MAS between two stream gauges (Arrigoni et al., 2010). We assumed that the climate impact would be similar between nested basins and any difference in streamflow is the result of anthropogenic influence between gauges. A time series subtraction analysis subtracts the streamflow in the upstream basin from the downstream basin. If the resulting residual time series is near zero, we assume the anthropogenic influence on mean annual streamflow is minimal (Arrigoni et al., 2010). We assume that increased directionality and variability of residuals point to larger anthropogenic influences between the upstream and downstream basin.

Subtraction analysis showed significant differences in streamflow between nested basins (Figure 3.13). Basin 15.1 generally had greater streamflow than Basin 15.12, perhaps reflecting the reduction in forest cover between the outlets of these two basins, which would result in more streamflow than evapotranspiration (Table 3.1). All major reservoirs were located upstream of Basin 15.12 (Figure 3.4); therefore, the residuals between basins cannot be attributed to reservoir storage. Residuals were near zero between Basin 15 and Basin 15.1, indicating little anthropogenic modification between gauges.

Residuals between Basin 16.2 and Basin 16.21 were always positive and increased over time. While uncertain of the cause for the large residual in the mid-1990s, the Q_H in the temporal Budyko analysis for Basin 16.2 increased from 1975 to a peak of 30% positive Q_H in the mid-1990s. In addition, the Budyko analysis found basin 16.2 had a 9% increase in Q_H relative to Basin 16.21's 10% decrease in Q_H during the period from 1970 to 2005, where the greatest increase in residuals occurred (Table 3.4). There were many potential direct human impacts to streamflow in Basin 16.21 as it was highly urbanized (30%), had large reservoir storage relative to its size, and over 90% of its water demand is met through surface water. The residuals between Basin 16.1 and Basin 16.11

were large (±10 cm, or 30% of MAS) but they fluctuated around zero. Q_H for the Budyko analysis supported the slight shift toward decreasing residuals observed from 1970 onwards as Basin 16.1 was estimated to have a -3% Q_H while Basin 16.11 had a +7% Q_H. Again, it is not clear what human modifications were driving these differences in streamflow. Basin 16.11 was small and highly urbanized (29%) relative to Basin 16.1's size (3 times larger) and urban land cover (12%). The large residuals between nested basins may reflect the fact that the ability for humans to significantly alter streamflow increases as basin size decreases because smaller basins tend to have distinctive characteristics (i.e. a dominant land type or activity) and are therefore more sensitive to anthropogenic impacts (Trimble and Weirich, 1987).

Basin 24 had significantly less streamflow than Basin 24.1. Both basins have large hydro-electric reservoirs immediately upstream of the gauge. The large difference in residuals is likely the result of reservoir operations. This analysis showed the range of impact (near zero to over 50% of MAS) Q_H can have on adjacent and nested streamflow.

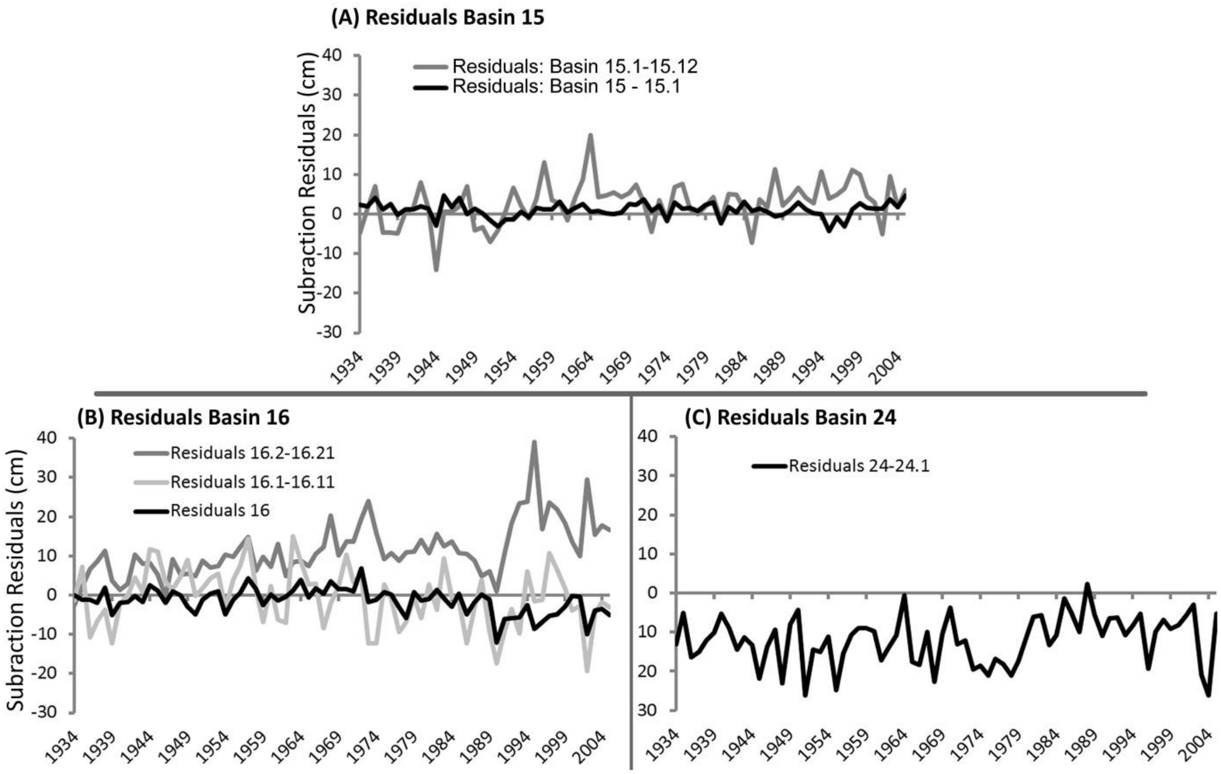


Figure 3.13: Subtraction residuals between nested basins. Residuals near zero mean there is little difference change in streamflow between gauges in the basin, and thus little anthropogenic influence between gauges. Decreasing residuals indicate that human modifications are decreasing streamflow between the upstream and downstream gauge. Positive residuals indicate that human modifications are increasing streamflow between upstream and downstream gauges.

3.10.6 Correlation between total change in Q and the climate / human induced contributions for the 5-yr moving average from 1970-2005.

Basin ID	Q_C:Q	Q_H:Q
1	0.86	0.62
2	0.70	0.44
3.1	0.75	0.25
3.2	0.87	0.43
3	0.70	0.51
5	0.63	0.77
11	0.67	0.28
12	0.78	0.31
15.12	0.90	0.24
15.1	0.92	0.55
15	0.90	0.37
16.11	0.67	0.49
16.1	0.65	0.50
16.21	0.39	0.67
16.2	0.65	0.58
16	0.72	0.55
17.1	0.85	0.87
17.2	0.70	0.81
17	0.89	0.90
20	0.70	0.38
21	0.81	0.86
24.1	0.68	0.88
24	0.73	0.87

3.11 References

Andreadis, K.M. and D.P. Lettenmaier. 2006. Trends in 20th Century Drought over the continental United States. *Geophysical Research Letters* 33 (L10403), doi: 10.1029/2006GL025711.

Arrigoni, A.S., M.C. Greenwood, and J.N. Moore. 2010. Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of river in the Northern Rocky Mountains, United States. *Water Resources Research* 46 (W12542), doi:10.1029/2010WR009162.

Arnold, C.L., and C.J. Gibbons, 1996. Impervious surface coverage: the emergence of a key environmental indicator. *Journal of the American Planning Association*, 62(2):243-258.

Barringer, T.H., R.G. Reiser, and C.V. Price. 1994. Potential effects of development on flow characteristics of two New Jersey streams. *Journal of American Water Resources Association* 30 (2): 283-295.

Bhaduri, B.L., E. Bright, P. Coleman, and M.L. Urban. 2007. LandScan USA: a high resolution geospatial and temporal modeling approach for population distribution and dynamics. *Geojournal* 69: 103-117.

Budyko, M.I. 1974. *Climate and Life*, Academic, New York. 508 p.

Campbell, J.L., C.T. Driscoll, A. Pourmokhatarian, and K. Hayhoe. 2011. Streamflow responses to past and projected future changes in climate at the Hubbard Brooke Experimental Forest, New Hampshire, United States. Water Resources Research 47, W02514, doi: 10.1029/2010WR009438.

Claessens, L., C. Hopkinson, e. Rastetter, and J. Vallino. 2006. Effect of historical changes in land use and climate on the water budget of an urbanizing watershed. *Water Resources Research* 42, W03426: 13, doi: 10.1029/205WR004131.

Degu, A.M., F. Hossain, D. Niyogi, R. Pielke, Sr., J.M. Shepherd, N. Voisin, and T. Chronis. 2011. The influence of large dams on surrounding climate and precipitation patterns. *Geophysical Research Letters* 38 (L04405), doi: 10.1029/2010GL046482.

Donohue, R.J., M.L. Roderick, and T.R. McVicar. 2007. On the importance of including vegetation dynamics in Budyko's hydrologic model. *Hydrol. Earth Syst. Sci.* 11, 983-995.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 28 (10): 2077-2080.

Forsythe, W.C., E.J. Rykiel Jr., R.S. Stahl, H. Wu, and R.M. Schoolfield. 1995. A model comparison for daylength as a function of latitude and day of year. *Ecological Modeling* 80: 87-95.

Franczyk, J. and H. Chang. 2008. Spatial Analysis of Water Use in Oregon, USA, 1985-2005. *Water Resource management* 23: 755-774, doi: 10.1007/s11269-008-9298-9.

Gleick, P. 2003. Water Use. *Annual Review of Environmental Resources* 28: 275-314, doi: 10.1146/annurev.energy.28.040202.122849.

Graf, W.L.. *1999*. Dam Nation: A Geographic Census of Large American Dams and Their Hydrologic Impacts. *Water Resources Research* 35: 1305-1311.

Hirsch, R.M. 2011. A perspective of Nonstationarity and Water Management. *JAWRA* 47 (3): 436-446. DOI: 10.1111/j.1752-1688.2011.00539.x

Hodgkins, G.A., R.W. Dudley, and S.S. Aichele. 2007. Historical changes in precipitation and streamflow in the U.S. Great Lakes Basin, 1915-2004: U.S. Geological Survey Scientific Investigations Report 2007-5118. p31.

Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology* 319: 83-95, doi: 10.1016/j.jhydrol.2005.07.003.

Kauffman, G.J. and K.J. Vonck. 2011. Frequency and intensity of extreme drought in the Delaware Basin, 1600-2002. *Water Resources Research* 47 (W05521), doi: 10.1029/2009WR008821.

Kim, Y. Forthcoming. Water yield change under climate and landuse/landcover variability in North Carolina Piedmont area. PhD dissertation at the University of North Carolina, Chapel Hill.

Krakauer, N.Y. and I. Fung. 2008. Mapping and attribution of change in streamflow in the coterminous United States. *Hydrol. Earth Syst. Sci* 12: 1111-1120.

Lettenmaier, D.P., E.F. Wood, J.R. Wallis. 1994. Hydo-climatological trends in the continental United States, 1948-88. *Journal of Climate* 7: 586-607.

Lins, J.F. and H.R. Slack. 2005. Seasonal and Regional Characteristics of U.S. Streamflow Trends in the United States from 1940 to 1999. *Physical Geography* 26 (6): 489-501.

Lu, J. G. Sun, S.G. McNulty, and D.M. Amatya. 2005. A Comparison of Six Potential Evapotranspiration Methods for Regional use in the Southeastern United States. *Journal of the American Water Resources Association* 41 (3): 621-633.

Ma, Z., S. Kang, L. Zhang, L. Tong, and X. Su. 2008. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. *Journal of Hydrology* 352, 239-249, doi: 10.1016/j.jhydrol.2007.12.022.

McCabe, G.J., J.L. Betancourt, S.T. Gray, M.A. Palecki, and H.G. Hidalgo. 2008. Associations of multi-decadal sea-surface temperature variability with US drought. *Quaternary International* 188: 31-40, doi:10.1016/j.quaint.2007.07.001.

McCabe, G.J., M.A. Palecki, and J.L. Betancourt. 2004. Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *PNAS* 101 (12): 4136-4141, doi: 10.1073/pnas.030678101.

McCabe, G.J. and D.M. Wolock. 2002. A step increase in streamflow in the conterminous United States. *Geophysical research Letters* 29 (24), 2185, doi: 10.1029/2002GL015999.

McCure, B. and J.B. Grace. 2002. Analysis of Ecological Communities. M;M Software Design. Gleneden Beach, OR. 299 pp.

Milly, P.C.D. 1994. Climate, soil water storage, and the average annual water balance. *Water Resources Research* 30 (7): 2143-2156, doi: 10.1029/94WR00586.zz

NCAGR (North Carolina Department of Agricultural and Consumer Services). 2011. Last accessed December 2011. http://www.ncagr.gov/agronomi/uyrst.htm.

Nisbet, T. 2005. Water Use by Trees. Forestry Commission, Edinburgh, UK. www.forestry.gov.uk

Patterson, L.A., B. Lutz, and M.W. Doyle. (Forthcoming). Streamflow changes in the South Atlantic, USA during the Mid and Late 20th Century. *Journal of American Water Resources Association*: 25.

Patterson, L.A. and M.W. Doyle. 2009. Assessing effectiveness of national flood policy through spatiotemporal monitoring of socioeconomic exposure. *JAWRA* 45 (1): 237-252.

Perlwitz, J., M. Hoerling, J. Eischeid, T. Xu, and A. Kumar. 2009. A strong bout of natural cooling in 2008. *Geophysical Research Letters* 36 (L23706), doi: 10.1029/2009GL041188.

Poff, N.L., J.D. Olden, D.M. Merritt, and D.M. Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. *PNAS* 104: 5732-5737.

Schilling, K.E., M.K. Jha, Y.K. Zhang, P.W. Gassman, and C.F. Wolter. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research* 44 (W00A09), doi: 10.1029/2007WR006644.

Small, D., S. Islam, and R.M. Vogel. 2006. Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? *Geophysical Research Letters* 33, L03403, doi: 10.1029/2005GL024995.

Sun, G., S.G. McNulty, J. Lu, D.M. Amatya, Y. Liang, R.K. Kolka. 2005. Regional annual water yield form forest lands and its response to potential deforestation across the southeastern United States. *Journal of Hydrology* 308: 258-268, doi:10.1016/j.jhydrol.2004.11.021

Tootle, G.A. 2005. Coupled oceanic-atmospheric variability and U.S. streamflow. *Water Resources Research* 41 (W12408), doi: 10.1029/2005WR004381.

Trenberth, K.E. 2011. Changes in precipitation with climate change. *Climate Research* 47: 123-138, doi: 10.3354/cr00953.

Trenberth, K.E. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* 42: 327-339.

Trimble, S.W. and F.H. Weirich. 1987. Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. *Water Resources Research* 23 (3): 425-437.

Urban, D.L. 2010. Multivariate Analysis: Ordinations on Ecological Distance. Pp 12.

Vörösmarty, C.J. 2000. Global water resources: Vulnerability from climate change and population growth. *Science* 289: 284-289. Doi: 10.1126/science.289.5477.284.

Wachob, A., A.D. Park, and R. Newcome,Jr. (eds). 2009. South Carolina State Water Assessment 2nd edition. South Carolina Department of Natural Resources, Columbia, SC. http://www.dnr.sc.gov/water/hydro/HydroPubs/assessment.htm. *Last Accessed September 2011.*

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47, W00J12, doi: 10.1029/2010WR010283.

Weiskel, P.K., R.M. Vogel, P.A. Steeves, P.J. Zarriello, L.A. DeSimone, and K.G. Ries III. 2007. Water use regimes: Characterizing direct human interaction with hydrologic systems. *Water Resources Research* 43 (W04402), doi: 10.1029/2006WR005062.

Xu, C.-Y. and V.P. Singh. 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes* 15: 305-319.

Zhang, L., K. Hickel, and W.R. Dawes. 2004. A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research* 40 (W02502), doi: 10.1029/2003WR002710

Zhang, L., W.R. Dawes, and G.R. Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* 37 (3): 701-708.

Zhu, Y. and R.L. Day. 2005. Analysis of streamflow trends and the effects of climate in Pennsylvania, 1971 to 2001. *Journal of American Water Resources Association* 41 (6): 1393-1405.

CHAPTER 4

CHARACTERIZATION OF DROUGHT SINCE THE 1930'S IN THE SOUTH ATLANTIC, US[3]

4.1 Abstract

Unlike the arid Western US, drought has not been extensively studied in the South Atlantic, nor have water allocation policies been thoroughly developed to address the potential for region-wide water scarcity. The goal of this study was to characterize hydrological drought – defined here as a deficit in streamflow - in the South Atlantic based on frequency, duration, streamflow deficit, severity, and spatial extent. We also determined whether there were significant changes in drought characteristics over three time periods: 1930-2010, 1930-1969, and 1970-2010. We found 71% of drought events were shorter than 6 months and 7% extended beyond one year. There were few significant temporal trends in drought characteristics during all three time periods to support the claim that drought is becoming more severe in the South Atlantic. The one exception is a significant increase in the spatial extent of drought, and an increase in the joint probability of adjacent basins being in drought conditions in the southern portion of the study area from 1970-2010.

4.2 Introduction

In North America, the drier climate west of the 100 meridian required water scarcity to be a central feature around which water management formed. Droughts, or a deficit in the normal

---

[3] Chapter 4 was co-authored with B. Lutz and M.W. Doyle and will be submitted to JAWRA

amount of water available, were a focus point of study because droughts exacerbated the problem of already limited water resources. The Southeastern United States has a humid climate (average annual precipitation of 70 to 180 cm; National Climate Data Center). As a result, both drought and water scarcity (not enough water to meet demand) have historically been of minimal concern. However, water scarcity was experienced in some eastern states along the Atlantic Coast following a multi-year drought that persisted from the late-1990s until 2002 (e.g. Kauffman and Vonck, 2011; Carbone and Dow, 2005; Weaver, 2005). Shortly thereafter, the Southeast U.S. experienced a second multi-year drought from 2006 to 2008 that resulted in widespread disruptions in water supply systems and over $1 billion in agricultural losses (Seager et al., 2009). The occurrence of back-to-back multi-year events has raised drought to a priority topic in at least two regards. The first is the need to characterize drought in the Southeast in order to understand its impact on water availability. The second is a need to determine if drought is becoming more prevalent in the Southeast (Sheffield and Wood, 2008).

Drought can be categorized as meteorological (deficit in precipitation), agricultural (deficit in soil moisture), hydrological (deficit in streamflow), and socioeconomic (an uncomfortable demand-supply ratio; Hill and Polsky, 2007; Wilhite & Buchanan-Smith, 2005). Meteorological droughts are often the catalyst for agricultural and hydrological droughts, which may be further exacerbated by human management of the landscape. However, considerable variability exists in the lag between departures in precipitation and when those departures become evident in streamflow. This variability is due to variation in basin characteristics and the influence of human land and water management (Wilhite & Buchanan-Smith, 2005). In this paper, we focus explicitly on hydrological droughts because municipal water supply systems in this area are predominantly surface water systems (e.g. 83% of North Carolina’s municipal population is served by surface water systems).

4.2.1 Drought characteristics, trends, and water management implications

Drought characterization of individual basins is important because it enables water managers to assess the potential impact of a drought through comparison with historic events and their corresponding impact on water resources (Andreadis et al., 2005). These characteristics include frequency (time between drought events), duration (length of drought), magnitude (cumulative streamflow deficit), and severity (integrates both magnitude and duration).

In addition to these traditional metrics used to describe droughts, there are also spatial characteristics attributable to drought events. Drought is a regional phenomenon that can impact multiple basins simultaneously and the spatial extent of droughts has regional implications for upstream and downstream water users, as well as for adjacent basins with water transfers. Thus, not only is it important to understand how drought impacts a basin, but also how water transfers between basins are potentially impacted.

Moreover, the time of year when droughts begin and end have different implications. For example, under normal conditions in the Southeast, streamflow tends to peak in winter months and is lowest during summer months, whereas demand is lowest in the winter and peaks in the summer months. Droughts that begin in the fall or winter limit groundwater and reservoir recharge, which can propagate impacts on streamflow during the summer months even if the summer receives normal amounts of precipitation. In contrast, a drought that begins in the summer intersects with peak water demand, which can exacerbate water scarcity. Water management decisions can benefit from a better understanding of how the temporal dynamics of drought interface with monthly hydrologic and human water use patterns.

In addition to better characterizing drought, long-term streamflow data (dating back to the 1930s) allows us to assess if there have been changes in drought characteristics through time. Climate forecasts predict that a warmer global climate will result in less frequent, but heavier precipitation events with longer dry periods in between (Trenberth et al., 2004). Warmer temperatures would also exacerbate drought by accelerating land-surface drying as higher temperatures evaporate more moisture (Dai et al., 2004).

Independent of changing drought characteristics, the baseline conditions within which droughts occur can alter their real and perceived impacts. Streamflow in the South Atlantic has not been stationary over much of the past century (Patterson et al., Forthcoming). Shifting climate patterns have resulted in the South Atlantic having more water in streams since the 1970s (relative to 1930-1969; Patterson et al., Chapter 3), while changes in human land use and water demands have resulted in streamflow reductions over time since 1970. Thus, two droughts with identical characteristics may have different consequences on water supplies at different points in time. As a result, our understanding of drought characteristics, or of how droughts have changed through time, must be interpreted within the context of the changes in mean streamflow conditions that have been previously identified.

4.3 Methods

4.3.1 Data

We analyzed streamflow data in the South Atlantic (basins draining to the Atlantic Ocean in North Carolina, South Carolina, and Virginia) from 1930 to 2010 (Figure 4.1). This time period allowed us to maximize our sample size while avoiding analyzing records of variable length (longer records were truncated to 1930). In addition, this time period included two of the most severe drought events that have occurred in the South Atlantic since instrumental record (early 1930s and 2006-2008). Previous studies found an abrupt increase in mean annual streamflow over much of the conterminous US around 1970 (Baines and Folland, 2007; McCabe and Wolock, 2002) that was also observed in the South Atlantic region (Patterson et al., Forthcoming). Thus, in addition to assessing drought events for the entire record, we also analyzed drought events separated into the drier "Mid-20th Century" (1930-1969) and the wetter "Late-20th Century" (1970-2005).

Monthly average streamflow data were acquired from the United States Geologic Survey (USGS) stream gauge network (http://nwis.waterdata.usgs.gov/nwis). Gauges having records from 1930 to 2010 with less than 10% missing data (n=54) were included in the analysis. All streamflow data were normalized by drainage area and converted to centimeters (cm).

4.3.2 Defining Hydrological Drought

While there is not a single definition for drought there are three decisions that can be made to define drought for analytical purposes: primary interest, time step of analysis, and how to distinguish drought events from a time series (Dracup et al., 1980). Our primary interest was hydrological drought. Hereafter "drought" refers to hydrological drought associated with low streamflow unless otherwise specified. We used monthly data to resolve drought events, similar to other drought studies (e.g. Wang et al., 2011; Sheffield et al. 2009, Andreadis et al., 2005). The statistical theory of runs (Yevjevich, 1967) was used to identify drought events. We defined a drought event as a deficit when streamflow falls below a threshold value (20th percentile for that month and site) that lasts for a minimum of three consecutive months (Sheffield et al., 2009; Andreadis et al., 2005). Similarly, we required three months of streamflow above the 20% threshold for a given drought event to terminate. This avoided having 1 or 2 months of streamflow above 20% split a long run of many dry months into separate events. This was particularly relevant for assessing drought in the Eastern US due to large month-to-month variability in precipitation and streamflow, indicating that dry (and wet) spells in this region are less persistent both temporally and spatially than in the central and western U.S (Andreadis et al., 2005). The definition of drought is sensitive to both the onset (3 consecutive months of drought) and termination (3 consecutive months of no drought) criteria (Appendix 4.9.1).

This conceptual definition of drought allows us to define an event relative to the normal conditions of a given basin (e.g. threshold values between basins are likely to differ; Sheffield et al., 2009) and month (e.g. winter typically has higher streamflow than summer months and drought would occur at different streamflow). As a result, a unique threshold value was assigned for each month in each basin (Figure 4.2).

We assessed other streamflow percentiles for defining drought conditions (21-30%, 11-20%, 6-10%, 3-5%, and <2%) and found that the 20% value used in similar studies was necessary to avoid having droughts becoming exceedingly rare (<10% threshold) or common (>30% threshold). We characterized five aspects of each drought event: frequency, duration, magnitude, severity, and spatial extent. Drought frequency (F) is defined as the inverse of the drought interval, or the number of months from the start of a drought to the start of the following drought (Wang et al., 2011). Duration (D) is defined as the number of consecutive months below a specific threshold (i.e. 20%; Shiau and Shen, 2001; Byun and Wilhite, 1999). Magnitude (also referred to as deficit) is defined as the cumulative deficit in streamflow in a drought event ($\sum Q_0 - Q$), where Q is streamflow (cm) and Q_o is the 20% streamflow threshold. Streamflow deficit should be comparable across the domain since streamflow has been normalized to basin size and the study area is limited to the South Atlantic. Drought severity measures the cumulative departure of streamflow percentiles from the 20th percentile threshold over the duration of drought ($100\% - \frac{\sum P}{D}$, where P is the percentile streamflow; Andreadis et al., 2005; Figure 4.2). The spatial extent of drought (A) is defined as the cumulative basin area in drought at a point in time. This metric extends beyond individual stream gauge characterization of drought and incorporates information from all gauges in our study area. Stream gauges integrate streamflow over spatial areas and are not capable of resolving the spatial variability of hydrological drought within the basin (Andreadis et al., 2005). Thus, our results for the spatial extent of drought are of limited value due to the relatively coarse spatial resolution of the basin (Figure 4.1).

Many studies have relied on the Palmer Drought Severity Index (PDSI) to define drought. PDSI is a meteorological drought index that was developed to standardize moisture conditions for comparison between regions (Palmer, 1965). This method was widely adopted in the United States; however, there are several limitations to using the PDSI (or Palmer Drought Hydrologic Index) for the study of hydrological drought. PDSI is highly sensitive to termination criteria and may lag emerging droughts by several months. It is also less well suited for areas with high precipitation variability (Andreadis et al., 2005), which is present in the South Atlantic (Patterson et al., Forthcoming). The Palmer indices have arbitrary criteria for determining drought characteristics (e.g. timing or severity) and there is not a basis for interpreting the resulting index values at different locations (Wang et al., 2011; Sheffield et al., 2009). For these reasons we use the percentile method and not the PDSI.

4.3.3 Trend Analysis

We analyzed changes in drought characteristics: frequency, duration, magnitude, and severity at each station using the non-parametric Mann-Kendall trend test (Hirsch and Slack, 1994). Mann Kendall (MK) tests provide information regarding the direction and significance of trends without making assumptions about normality or linearity (Hirsch and Slack, 1984). MK has been used to calculate trends in characteristics for a time series of drought events (e.g. Wang et al., 2011, Sheffield and Wood, 2008; Andreadis and Lettenmaier, 2006). We calculated the median slope for all pairwise selections of drought events in each time series to get an estimate of the magnitude of change. The MK test was applied to a time series of drought events for each stream gauge. Trends in the spatial extent of drought were calculated each month from 1930 to 2010 in the South Atlantic to create a time series for the MK test (spatial adjacency was not required). The trend analyses were calculated for the entire period, Mid-20th Century (1930-1969), and Late-20th Century (1970-2010).

4.3.4 Probability of Coincident Drought Conditions

Droughts are spatial phenomena that have regional implications. To quantitatively analyze spatial characteristics of drought, we calculated the joint probability of basins in our study area being in drought at the same time.

First, we calculated the probability of each basin being in drought conditions over the time series. $P_d = \frac{\sum D}{N}$, where P_d is the probability of the basin being in drought, D is the number of drought months, and N is the total number of months in the time series.

We then calculated the conditional probability of one basin being in drought given that another basin is already in drought conditions. $P_{dd} = P(\frac{\sum D_j}{N_i} \mid D_i)$, where P_{dd} is the probability of two basins simultaneously in drought, D_i is the condition of the first basin being in drought, D_j is the number of months where the second basin was in drought at the same time the first basin was in drought, and N_i is the number of months the first basin was in drought condition.

We calculated the joint probability of a pair of basins being in drought over a time series (includes temporal and conditional component) to assess the overall probability of drought between paired basins. The joint probability was the product of the percent of time a basin is in drought and the conditional probability ($P_d P_{dd}$).

The above probabilities were calculated for the entire, Mid-20th, and Late-20th Century to assess changes in the spatial variation of regional drought. A correlation matrix was created to compare each basin with the remaining 53 basins. Paired student t-tests were used to calculate the significance of changes in probabilities for all basins between each time period.

4.4 Results

4.4.1 Drought Characteristics

Almost three quarters (71%, n=746) of drought events in our study basins within the South Atlantic between 1930 and 2010 had durations of less than six months (Table 4.1). Approximately 7% of drought events exceeded one year (n=35) and 1% exceeded two years (n=7). While the frequency of events declined as duration increased, the average number of years between drought events (i.e., recurrence interval) peaked for droughts with 12 to 14 month durations. There was an average of 5.6 years between droughts less than 6 months and 42.8 years between 12 to 14 month droughts. Recurrence intervals for droughts exceeding 14 months varied widely because these events are rare and, thus, our uncertainty in their estimates is high. Drought severity followed a similar pattern as recurrence intervals, peaking for droughts of intermediate duration (Table 4.1). The average streamflow deficit increased as the duration of the drought progressed, but was fairly low for events shorter than 12 months (<=5.1 cm).

Droughts with longer duration were more common during the Late-20th compared to the Mid-20th century (Appendix 4.9.3). Over 97% of all drought events that exceeded 15 months (32 events) and 76% of all drought events that exceeded one year (59 events) occurred between 1970 and 2010. Conversely, droughts with shorter durations (<9 months) occurred with greater frequency during the Mid-20th Century. There were not significant differences in drought characteristics for events shorter than 14 months between the Mid- and Late-20th Century.

Drought events shorter than 6 months had a greater tendency to start in the fall and winter (Figure 4.4). Droughts lasting between 6 months and a year were more likely to begin in the late winter and August. Droughts exceeding one year were most likely to begin in early fall. The termination of drought events shorter than 6 months was fairly evenly distributed from March to November, with a slight peak during months of high hurricane activity (August – October). In contrast, droughts lasting more than a year were most likely to end in late spring / early summer and during peak hurricane activity. Drought events were least likely to terminate in December and January.

4.4.2 Trend Analysis

While drought frequencies and durations differed significantly between Mid- and Late-20th centuries, within each time period there were few significant trends in any drought characteristic (Figure 4.5). The greatest number of trends (n=5; 9%) over the entire period occurred with respect to an increase in the streamflow deficit experienced during drought events. The absence of significant trends during any of these time periods suggests there have not been significant, regional changes in drought observed over the last 30 to 80 years.

4.4.3 Spatial trends and drought probabilities

The above trend analysis of drought characteristics was applied to individual sites. We now combined sites to assess trends in the spatial coverage of drought for this region. The MK test for the entire period and Mid-20th Century did not show a significant change in drought coverage over time (p=0.16 and 0.96, respectively; Figure 4.6). The Late-20th Century had a significant increase in the percent of our study area in hydrological drought ($p<0.001$).

Over the entire period (1930-2010), basins were on average in drought 11% of the time (range: 3% to 15%; Table 4.2). We did not find a significant difference in the probability of a basin being in drought conditions between the Mid-20th (10±3%) and Late-20th Century (11±4%). Across all possible pairwise comparisons, the mean conditional probability, or the probability that two basins were simultaneously in-drought was 41±14% for the entire period (Table 4.2). The conditional probability was significantly lower in the Mid-20th Century (36±18%) compared to the Late-20th Century (46±18%; $p<0.001$). For all pairwise comparisons we also calculated the probability that two paired basins will be in drought at any given time (joint probability), which was 4.4±0.8% for the entire record. Similar to the patterns in conditional probabilities, joint probabilities were lower in the Mid-20th Century (3.8±1.2%) and higher in the Late-20th Century (4.9±1.4%; $p<0.001$; Appendix 4.9.5).

We explored the spatial variation in changes of conditional and joint probabilities by looking at differences between nested and adjacent basins from the Mid- to Late-20th Century (Figure 4.1; Table 4.3; Appendix 4.9.5). We found that nearby basins in the northern portion of the study area had a decrease in conditional and joint probabilities from the Mid- to Late-20th Century. For example, Basin 3's joint probability indicated that on average 12% of all three basins were simultaneously in drought during the Mid-20th Century, compared with 6% during the Late-20th Century. In contrast, nearby basins in the southern portion of the study area had an increase in conditional and joint probability between these time periods. For example, Basin 24 and 24.1 increased from a joint probability of 1% in the Mid-20th to 11% during the Late-20th Century. The different joint probabilities between time periods may indicate a shift in regional drought patterns.

4.5 Discussion

4.5.1 Drought characterization

The most common hydrologic drought in the South Atlantic is best characterized as being short in duration (less than 6 months) and occur typically over 5 years apart (Table 4.1). These events most commonly began between late summer and winter, which extends into peak groundwater and reservoir recharge months. In order to provide some context for streamflow deficit and water management we talk about the impact of drought in terms of deviation from median conditions (the amount of water normally available) in the discussion, rather than the 20% threshold definition used to define drought. Average annual streamflow across the study basins was 51.9±12.2 cm. The average deficit from median streamflow conditions for droughts less than 6 months was 6.5 cm

(13% of mean annual flow). The short duration poses little risk of resulting in socioeconomic drought or interfering with meeting water demand (i.e. most water supply reservoirs hold more than 5 months of water).

This region experienced a drought lasting between 6-12 months on average once every two to three decades (Table 4.1). The average deficits of 6-8 months droughts from median streamflow (13.4 cm) and 9-11 months (18.5 cm) account for 26% to 36% of mean annual streamflow, respectively. Moreover, these events typically began during late winter / early spring and terminated during the fall, which encompasses the growing season for plants, peak water demand, and low summer streamflow (Figure 4.4). Given their magnitude and timing, these droughts of intermediate duration may have perceivable impacts on water availability.

Droughts lasting more than a year were rare, with sites uncommonly experiencing more than one to three of these events over the 80 year record. For droughts lasting 12-14 months, the average deficit was 26 cm (50% of mean annual streamflow), and for droughts lasting more than 2 years the average deficit was 74 cm (71% of two years of annual streamflow). These deficits approach annual streamflow volumes and can require many months of above average streamflow conditions to compensate for these large deficits. Prolonged drought events through time were often spatially expansive. These events have the capacity to produce wide-spread socioeconomic drought, whereby water demand cannot be met without extensive water management and conservation efforts (e.g. Hill and Polsky, 2007).

4.5.2 Drought probabilities and spatial trends

When drought conditions were present in the South Atlantic, the spatial extent of drought covered an average of 28±27% of the study area. The range of drought coverage extended from 0% to 100% (e.g. Figure 4.7 for an example of spatial variation in drought extent). We found a significant increase in the spatial extent of drought during the Late-20th Century (Figure 4.6). Changes in the spatial extent of droughts are likely driven by regional changes in climate. While anthropogenic factors, such as consumptive water use, land use changes, irrigation, and reservoirs (e.g. Wang and Hejazi, 2011; Arrigoni et al., 2010) do not initiate droughts, they may contribute to prolonged and more severe drought events (Kauffman and Vonk, 2011; Hill and Polsky, 2007). For example, intensive reforestation during the 1950's resulted in higher evapotranspiration rates that exacerbated hydrologic drought conditions relative to a previous drought in the early 1900s that had more runoff with less precipitation (Trimble and Weirich, 1987).

While anthropogenic modifications can amplify or reduce the incidence of our definition for hydrological drought, the region-wide shift in drought patterns indicates a dominant climate component (Table 4.3). The spatial trend in drought is consistent with Patterson et al.'s (Forthcoming) spatial pattern of increasing (decreasing) average streamflow in the northern (southern) portion of the study area during the Late-20th Century. Here, we found the northern portion of the study area to have higher conditional and joint probabilities of being in drought conditions during the Mid-20th Century; whereas the southern portion had greater probabilities in the Late-20th Century. The increased joint probability of basins being in drought in the southern portion of the study area is concerning because this implies that nearby basins, which are potential sources for emergency water supply, have an increased likelihood of simultaneously being in drought conditions.

4.5.3 Climatic drivers of multi-year drought events and drought trends

The irregularity of persistent, multi-year droughts is due to the high variability in precipitation experienced in the Southeast, US (Seager et al, 2009; Andreadis et al., 2005) and the frequency of high precipitation, tropical storm events (approximately one event every 1 to 3 years; Konrad, 2002). Most drought events lasting more than one year, and all multi-year drought events, have occurred since 1970. Major drought events in the region did occur prior to 1970, including the

1930's dustbowl and the continental scale drought of the 1950's. However, both of these drought events experienced intermittent recovery and relief from drought conditions due to occasional precipitation events (Andreadis et al., 2005). In contrast, the multi-year drought events in 1998-2002 and 2006-2008 experienced little relief from drought events and resulted in record low streamflow (Seager et al., 2009; Weaver, 2005).

Drought is generally driven by extremes in the natural variation of climate, which are forced through atmospheric interactions and feedbacks with sea surface temperature (McCabe et al., 2008; Sheffield and Wood, 2008; McCabe and Palecki, 2006). Drought persistence has been predominantly linked to land-atmosphere feedbacks that can be mitigated or exaggerated by human activities and warmer temperatures (Sheffield et al., 2009). Anthropogenic factors, such as high water demand, may also be playing a more significant role in the Southeast, U.S. (Carter et al., 2008).

While multi-year droughts have not been the norm for the South Atlantic over the last century due to high precipitation variability and tropical storm activity, paleo-climatic reconstructions of streamflow provide evidence for droughts lasting up to 20 years (Seager et al; 2009; Woodhouse and Overpeck, 1998). The instrumental record represents only a small subset of historical droughts, but it is within that subset that infrastructure decisions and water allocation policy have been made. The reality is that the South Atlantic region, under some climate regimes, has the capacity to undergo decadal droughts similar to those experienced by the more arid regions in the western U.S.

In spite of the major drought events (>18 month duration) that occurred at the end of our period of record, we found few significant trends in drought characteristics over the entire period and the Late-20th Century (Figure 4.5). Our findings of few trends in duration and severity were similar to those of Andreadis and Lettenmaier (2006) for the South Atlantic region.

While there were few significant trends in drought characteristics, there have been significant trends in mean streamflow in the South Atlantic during the Late-20th Century (Patterson et al., Forthcoming). There are two plausible explanations for why a significant change in mean streamflow has been observed without a corresponding increase in drought prevalence and deficit. First, the time series of drought events has fewer values per station (average of 11 events per site compared to 420 streamflow values for the Late-20^{th} Century). The smaller sample size reduces confidence in the significance of a trend. Second, the trend of decreasing streamflow during the Late-20^{th} Century is within the context of an overall wetter hydrological regime relative to the Mid-20^{th} Century (Patterson et al., Chapter 2). Thus, despite the decline in average streamflow during the Late-20^{th} Century there is more water available in the streams than was present during the Mid-20^{th} Century.

Each watershed has a time series, or a context, within which a shock (e.g. drought) occurs and each watershed is spatially located in relationship to other basins and potential water transfers. While drought characteristics have not significantly changed over time, the context within which drought occurs has changed in at least two important ways since the 1970s. First, nearly all sites had decreasing streamflow (by an average of 7±10%). Second, the South Atlantic experienced rapid population and industrial growth since the 1970s that has led to increased water demand (e.g. Carbone and Dow, 2005; Figure 4.8) that places additional stress on water resources and can exacerbate the effects of drought. The general context of decreasing average streamflow and increasing water demand may effectively result in streams becoming more "drought sensitive" (often observed by an increase in deficit relative to duration) and it may take longer for streams to recover as reservoirs re-fill (Hill and Polsky, 2007).

The warming climate has brought attention to the possibility of an increase in more extreme hydrologic events such as floods and droughts (e.g. Trenberth, 2011; Karl et al., 2009). An increase in the frequency of drought is concerning, particularly if the recovery time of reservoirs begins to exceed the frequency of events (Figure 4.9A). However, the context within which drought events occur is also important to consider. For example, the decrease in streamflow observed in the South

Atlantic may result in longer reservoir refill times even though there has been no change in drought characteristics. Thus, it is important to consider not only potential changes in drought, but also changes in the context within which drought occurs (both water supply and demand).

4.6 Conclusion

Rapid population and industrial growth in this region since the 1970's has continued to put pressure on limited water supplies in the South Atlantic (e.g. Feldman, 2009). Understanding drought characteristics is essential to effectively mitigate the impact of drought on water supply systems (Shiau et al., 2001), particularly surface water supply systems. We found droughts are typically of short duration (less than 6 months), but there have been droughts extending up to three years at some locations. It is the occurrence of these multi-year drought events that is of growing concern in the South Atlantic (Carbone and Dow, 2005). Despite the presence of two region-wide drought events in 1998-2002 and 2006-2008, there were few significant trends indicating an increase in drought frequency, duration, deficit, or severity over the time periods examined. However, there was a significant increase in the spatial extent of drought for our study area from 1970-2010, particularly in the southern portion of the South Atlantic.

Droughts are economically and environmentally costly due to their large spatial extent and lengthy duration (Wilhite, 2000). Typically, water managers assess the potential impact of drought by comparing current or potential drought severities with historical drought events for their particular basins. While useful, this method overlooks the impacts of the spatial extent of drought (Andreadis et al., 2005). We found the conditional probability of basins simultaneously being in drought increased during the Late-20th Century. Interconnections between water utilities in adjacent basins are one management strategy to redistribute water and alleviate a water supply shortage. However, this water management strategy will not be useful if basins are suffering similar water shortages due to drought. Further work is needed to understand the probability of adjacent basins being in similar drought conditions and the implications to current and future interconnections.

4.7 Tables

Table 4.1: Characteristics for droughts of different duration. Mean values ± standard deviation are reported (median values had similar values). An event does not take regional drought into consideration, but is simply the number of droughts of that duration that occurred between all sites.

Duration (months)	Number Events	Mean Events Per Site	Mean Recurrence Interval	Mean Severity (%)	Mean Deficit (cm)
3 to 5	746	13.8, (3.4)	5.6, (5.5)	91.5, (3.8)	1.8, (1.4)
6 to 8	156	3, (1.5)	18.1, (14.0)	92.8, (3.1)	4.1, (2.2)
9 to 11	77	1.9, (1.0)	28.1, (22.6)	92.6, (3.1)	5.1, (2.4)
12 to 14	45	1.4, (0.5)	42.8, (30.8)	94.2, (2.4)	8.7, (3.1)
15 to 17	19	1.2, (0.4)	14.7, (15.1)	92.8, (2.3)	8.7, (4.5)
18 to 23	7	1.2, (0.4)	19.8, (NA)	92.3, (3.1)	17, (9.7)
24 to 35	7	1, (0)	---, (---)	90.9, (1.4)	25.1, (11.2)

NA: only one site experienced two drought events between 18 and 23 months

--- : droughts exceeding two years were not experienced more than once at any site

Table 4.2: Average probabilities for all 54 basins by time periods. Average ± standard deviation. The range of individual basin values is below in parentheses.

	1930-2010	**1930-1969**	**1970-2010**
Probability (Time in drought)	11% ± 2% (3%-15%)	10% ± 3% (4%-16%)	11% ± 4% (3%-20%)
Conditional (Two basins both in drought)	41% ± 14% (5%-86%)	36% ± 18% (0%-100%)	46% ± 18% (0%-100%)
Joint (Conditional * Probability)	4.4% ± 0.8% (1.9%-5.7%)	3.8% ± 1.2% (1.3%-5.9%)	4.9% ± 1.4% (1.2%-7.4%)

Table 4.3: Changes in conditional and joint probabilities for nested basins from the Mid to Late-20th Century.

	Conditional Probability			**Joint Probability**		
Nested Basins	**Mid-Century**	**Late-Century**	**Change**	**Mid-Century**	**Late-Century**	**Change**
Group 3	75%	65%	-10%	12%	6%	-6%
Group 4	79%	82%	3%	9%	9%	0%
Group 5	64%	52%	-11%	8%	4%	-4%
Group 9	82%	85%	3%	11%	7%	-4%
Group 12	41%	65%	24%	4%	8%	4%
Group 15	66%	53%	-13%	6%	6%	0%
Group 16	44%	59%	16%	4%	5%	1%
Group 17	38%	68%	29%	3%	10%	6%
Group 24	18%	60%	43%	1%	11%	10%
Average	**56%**	**66%**	**9%**	**7%**	**7%**	**0%**

4.8 Figures

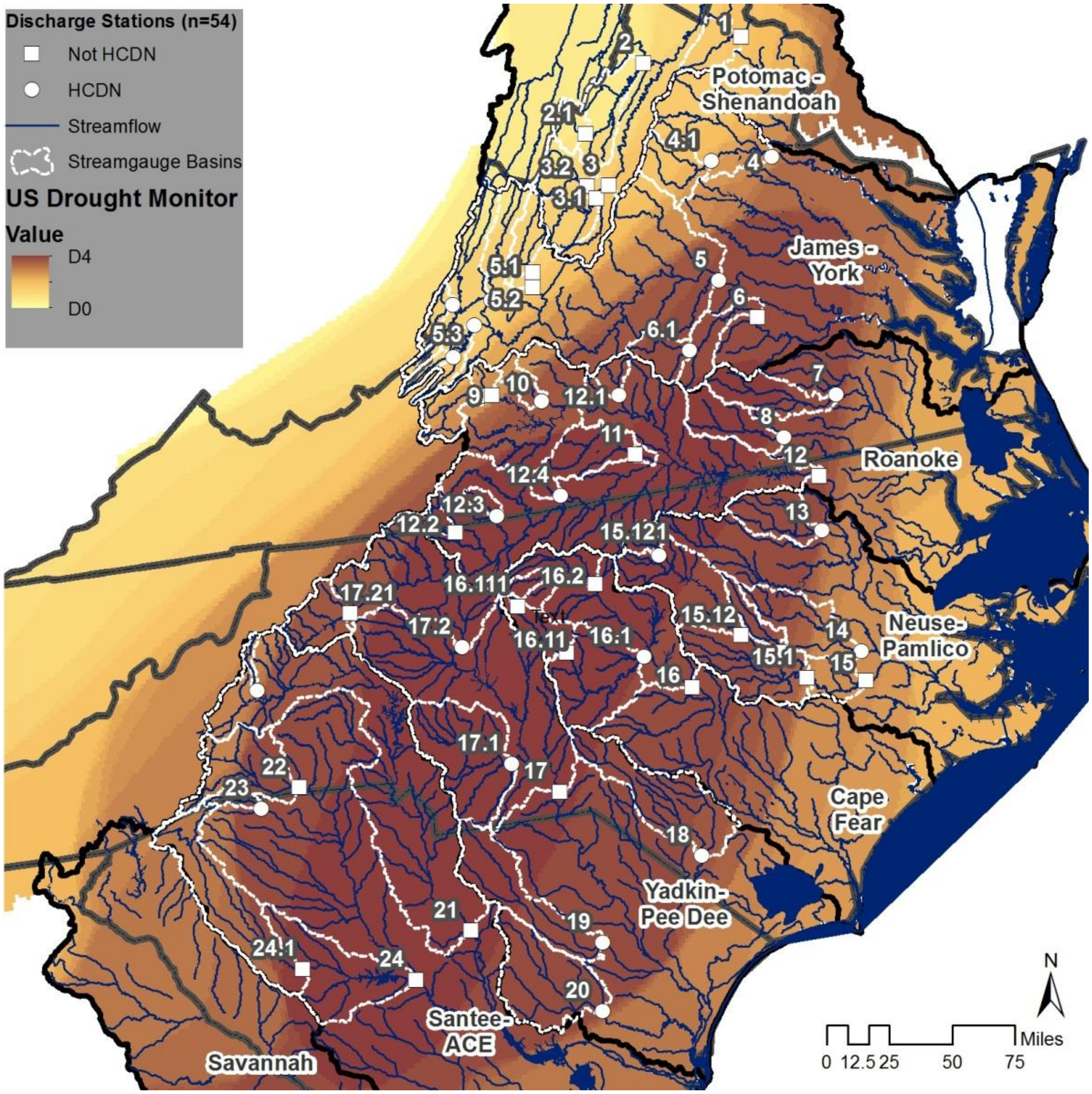


Figure 4.1: Stream gauges and their representative basins in the South Atlantic. The background is the US Drought Monitor classification of drought conditions in July 2002 for illustrative purposes.

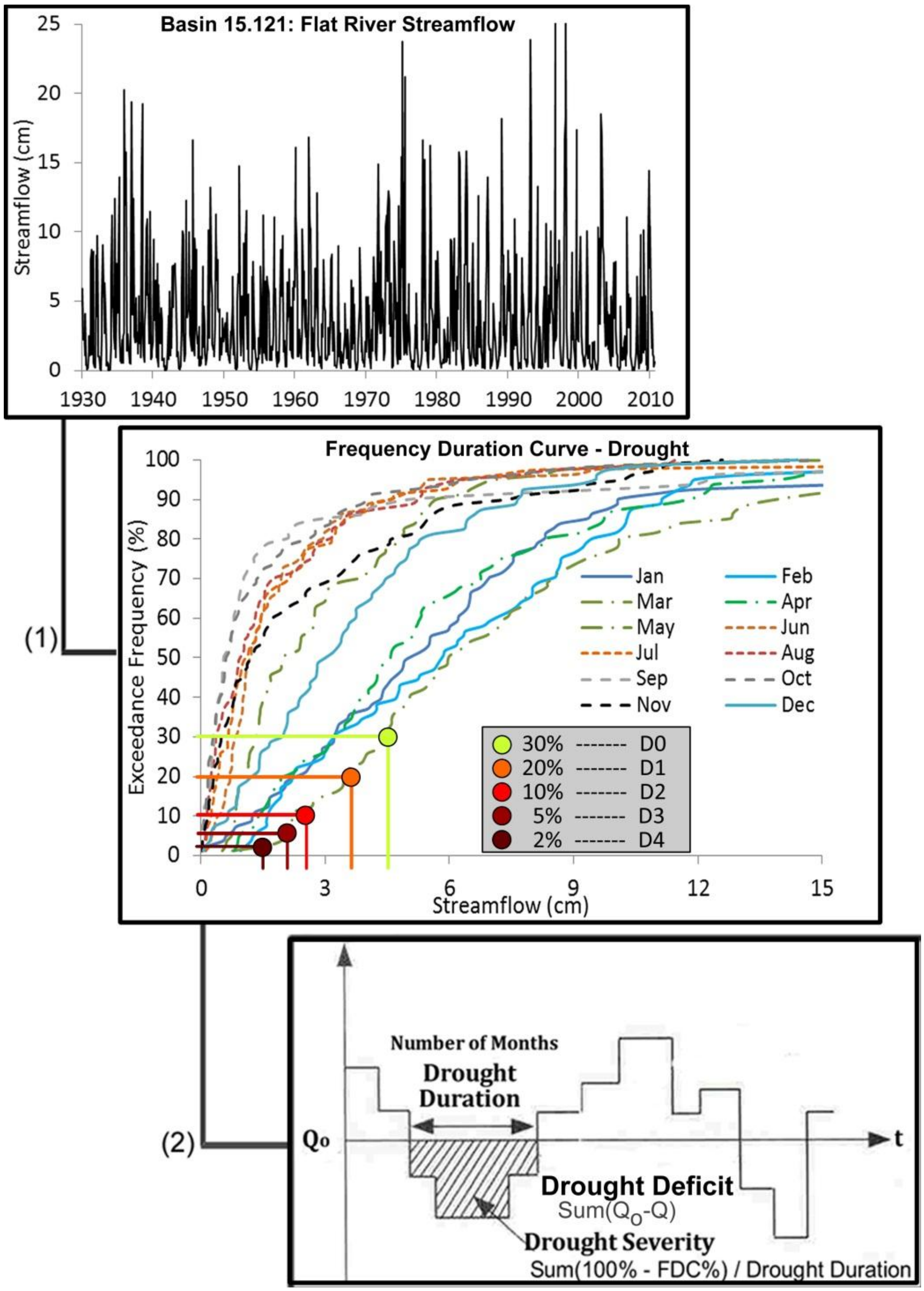


Figure 4.2: Method for calculating hydrological drought characteristics. (Top) Monthly streamflow time series. (Middle) Monthly percentiles were flagged for different drought categories. (Bottom) Drought characterization in the time series.

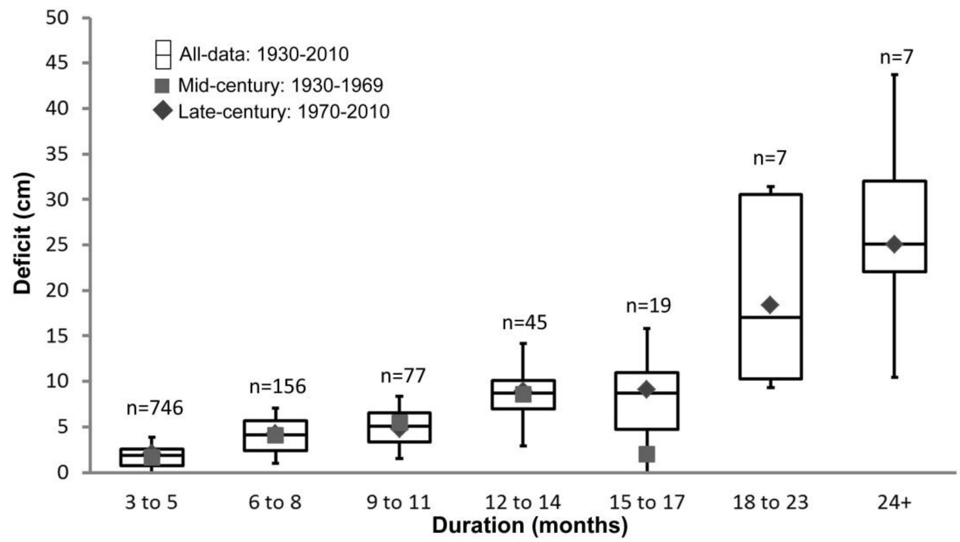


Figure 4.3: Average deficit for a given duration bin. Box plot is for all data (25-75 percentiles). Error bars are 10 and 90 percentiles. Average deficit is shown for Mid-20th and Late-20th Century droughts.

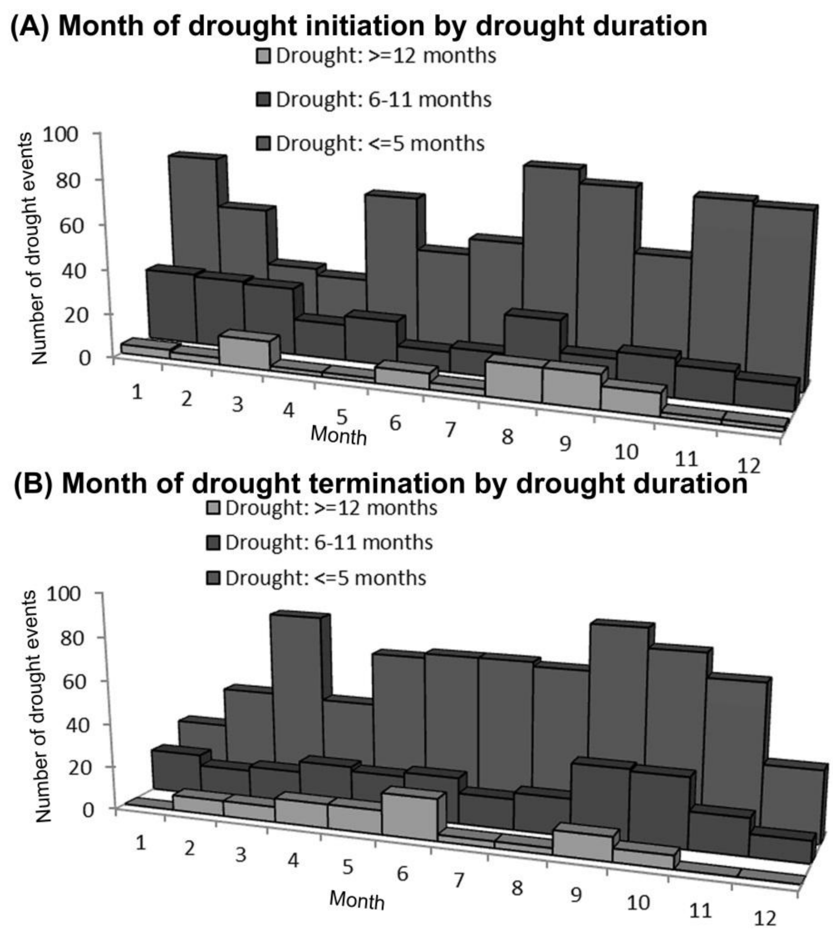


Figure 4.4: The number of drought events that began (A) and ended (B) in the study area between 1930-2010. Categories are by drought duration.

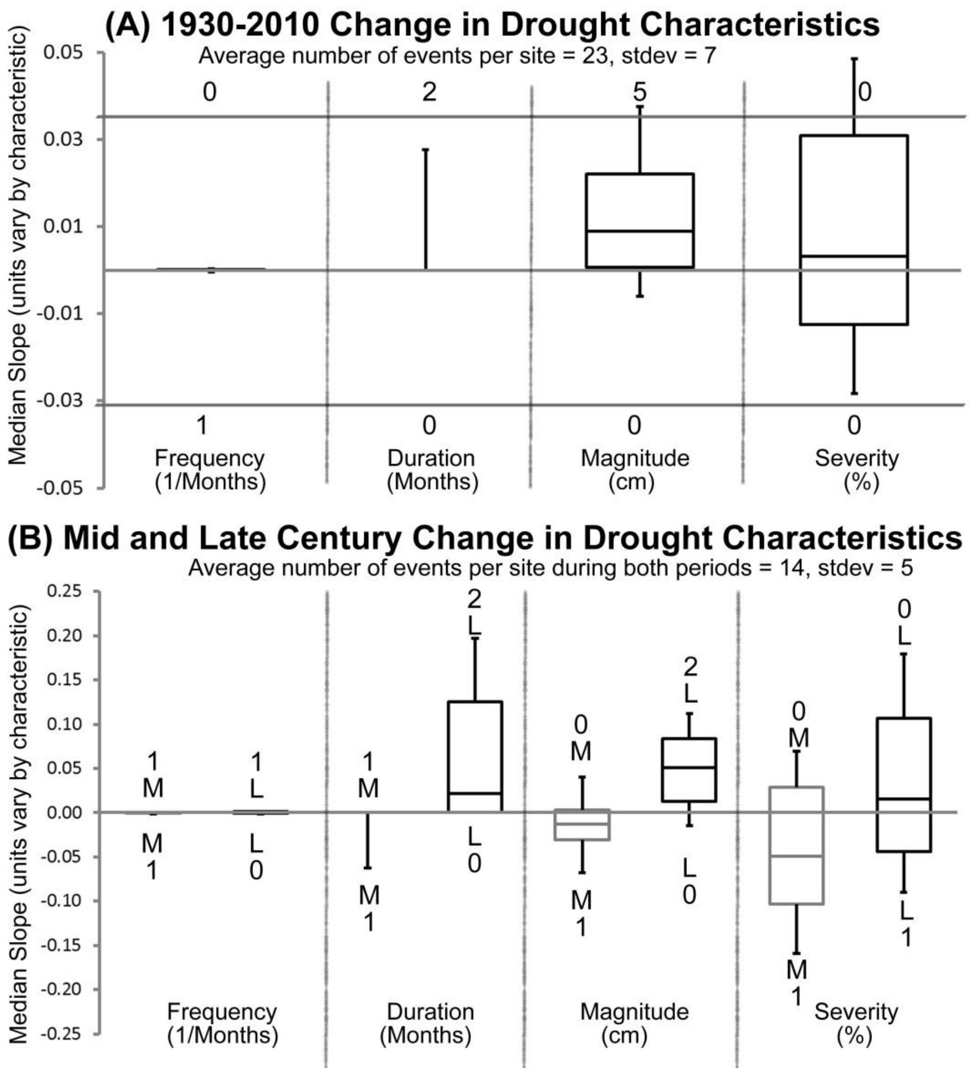


Figure 4.5: Trends in drought characteristics. Box plot of trend slopes for all 54 sites are shown with the number of significant sites with trends displayed above (increasing) and below (decreasing) the respective box plot. (A) Trends during the entire period (1930-2010). (B) Trends in mid-century (M) and late-century (L) drought characteristics. All increasing values indicate an increase in that drought characteristic (drier).

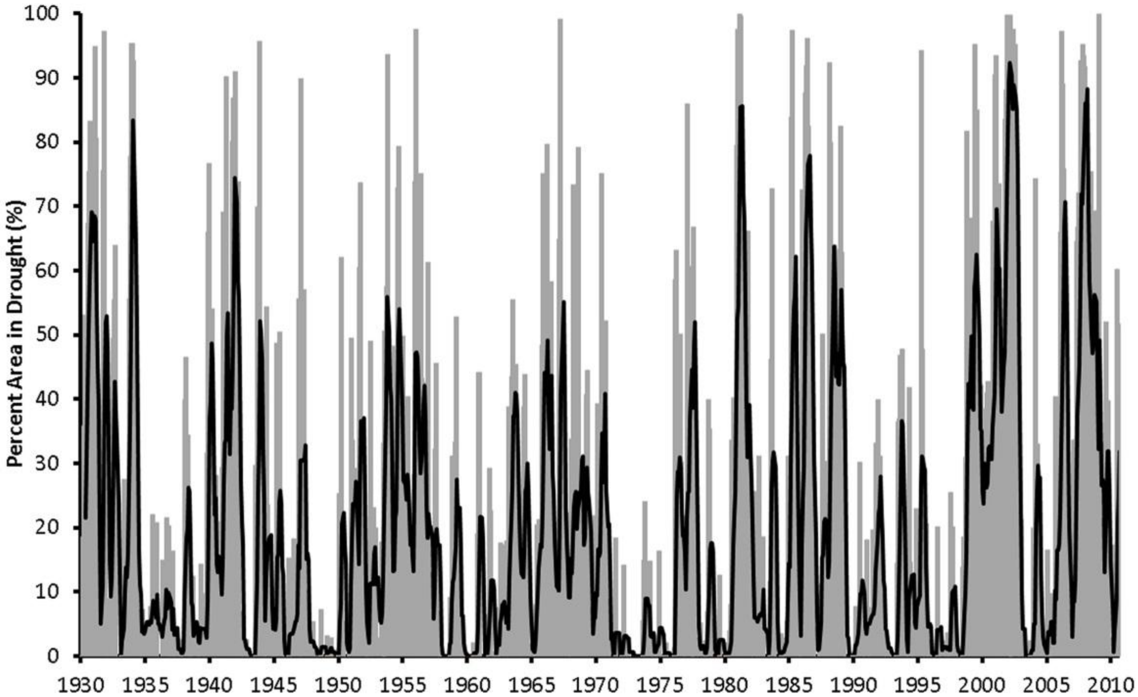


Figure 4.6: Percent of study area in drought over time. Black line is a 5 month moving average.

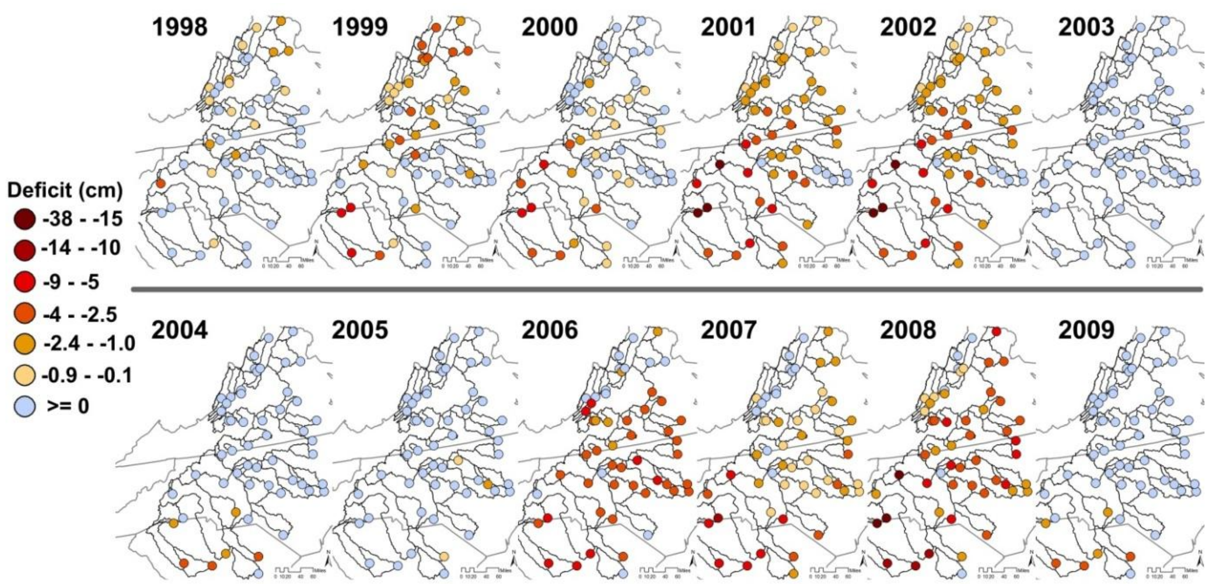


Figure 4.7: Maximum streamflow deficit in a given year (not by drought event) to see the spatial distribution of two multi-year droughts (1999-2002 and 2006-2008).

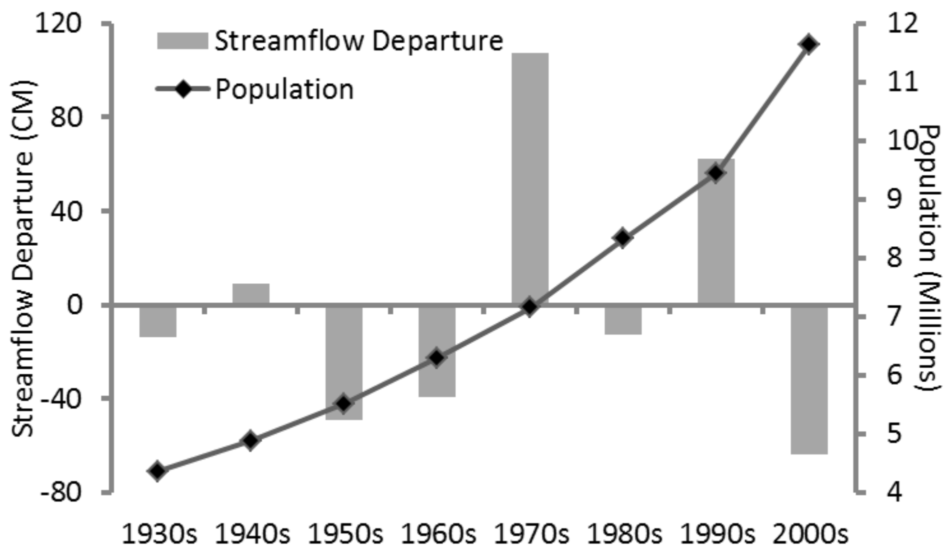


Figure 4.8: Population has continued to increase in this region since the 1970's with an acceleration population growth since the 1990's. This has increased water demand. Average streamflow, or water supply, has been more variable over time. The challenge is to manage water resources for a growing population and fluctuating supply.

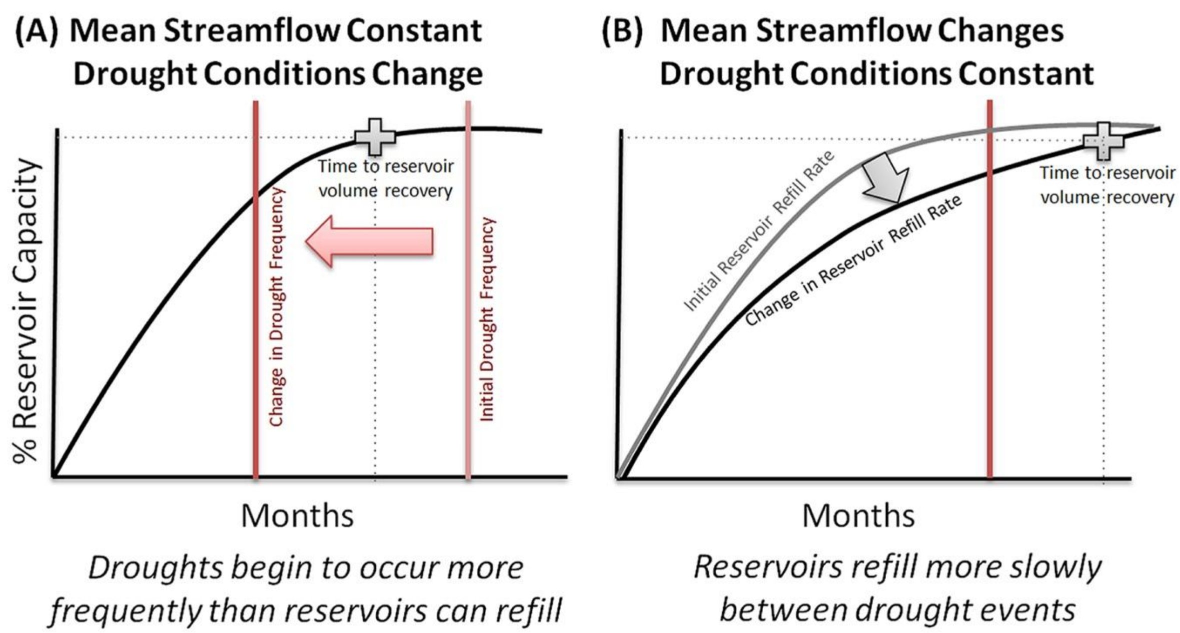


Figure 4.9: Schematic illustrating the impact of (A) change in drought and (B) change in mean streamflow on reservoir refill times. (A) An increase in drought frequency causes drought events to occur at intervals that exceed reservoir refill rates. (B) Drought characteristics remain constant, but the decrease in mean streamflow, or the context, within which drought occurs results in longer reservoir recovery times.

4.9 Appendix

4.9.1 Streamflow and Precipitation by Percentiles

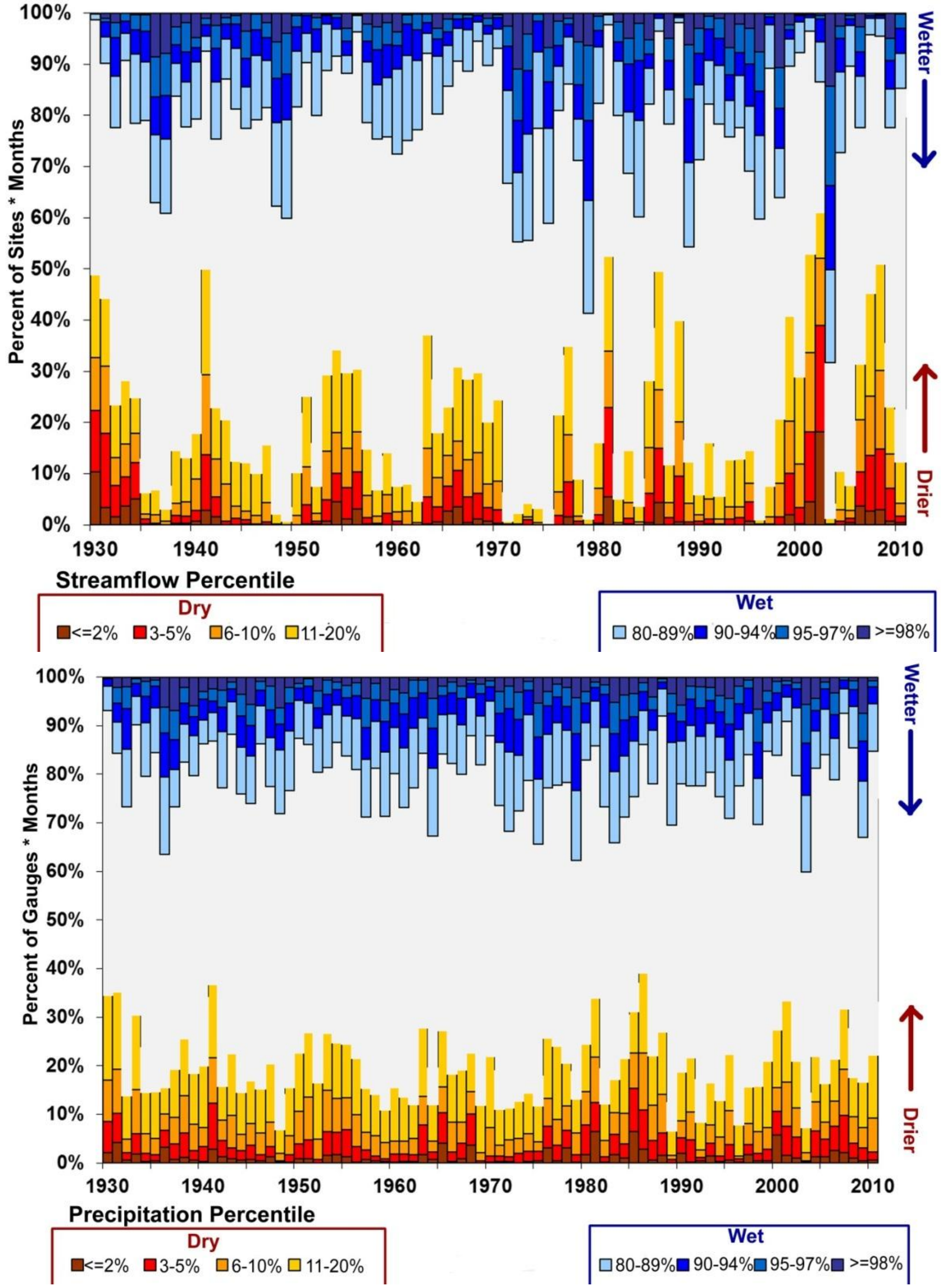


Figure 4.10: (Top) Hydrologic percentile streamflow showing distinct periods of dry and wet spells using the 20% threshold. (Bottom) In contrast precipitation has little distinction due to high variability and limited atmospheric system memory (monthly time-scale is too long).

4.9.2 Drought sensitivity to onset and termination criteria

The number of drought events exponentially decreases as the number of months required to start a drought increases. Many studies use 3 consecutive months (e.g. Sheffield and Wood, 2008; Andreadis et al., 2005) and served as the impetus for our 3 month decision. The number of drought events was less sensitive to the termination criteria (linear decrease). Anything shorter than 3 months did not match the “societal” definition of drought during the last two events; therefore, we selected 3 months as our termination criteria. At some sites the three month criteria still resulted in two or three separate drought events from 1998-2002.

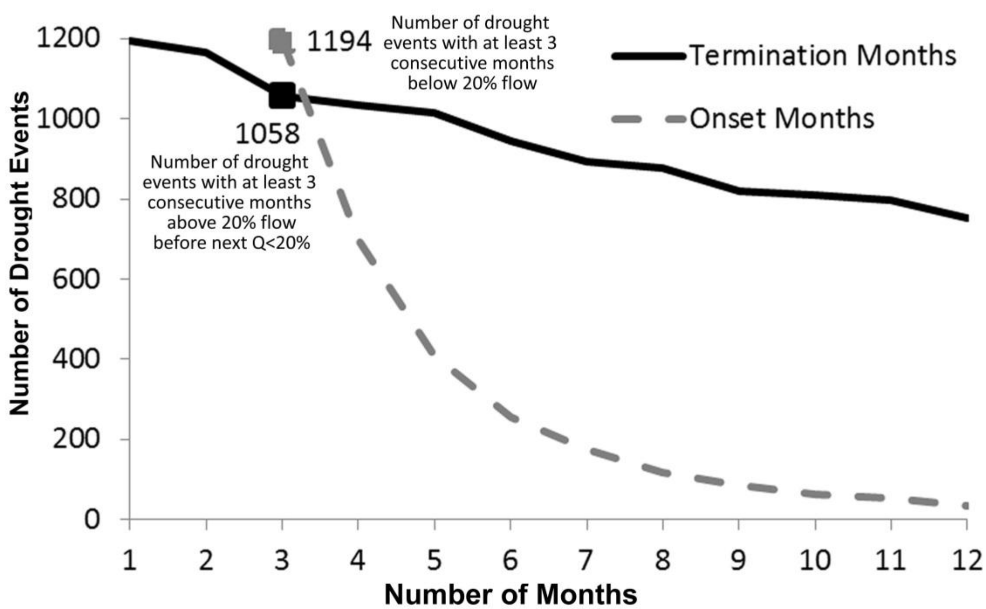


Figure 4.11: Sensitivity of drought to onset and termination criteria. The number of drought events exponentially decreases as the onset month criteria increases. The number of drought events linearly decreases as termination month criteria increases.

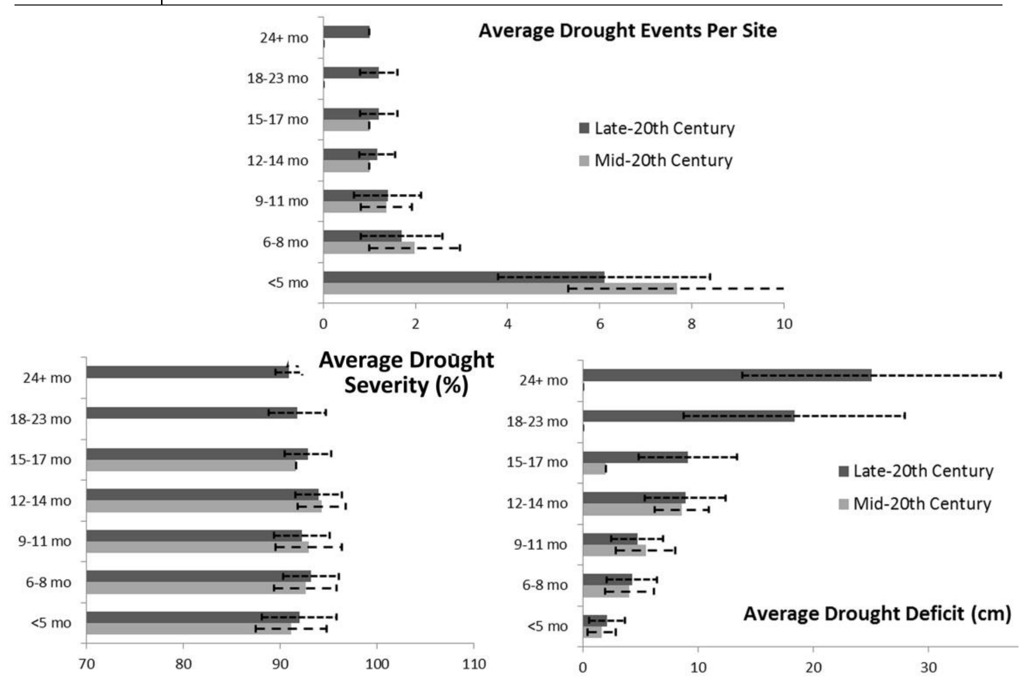
4.9.3 Drought characteristics for Mid- and Late-Century

Table 4.4: Mid-20th century drought characteristics. NA – Not enough events per site to calculate a standard deviation. See Figure below for comparison with Late-20th century.

Duration (months)	Number Events	Mean Events Per Site	Mean Severity (%)	Average Deficit (cm)
3 to 5	414	7.7, (2.4)	91.1, (3.7)	1.6, (1.2)
6 to 8	93	2.0, (1)	92.6, (3.2)	4.0, (2.1)
9 to 11	37	1.4, (0.6)	92.9, (3.4)	5.5, (2.6)
12 to 14	18	1.0, (0)	94.3, (2.5)	8.6, (2.4)
15 to 17	1	1.0, (NA)	91.7, (NA)	2.0, (NA)
18 to 23	0	0, (NA)	NA, (NA)	NA, (NA)
24+	0	0, (NA)	NA, (NA)	NA, (NA)

Table 4.5: Late century drought characteristics. See Figure below for comparison with Mid-20th century.

Duration (months)	Number Events	Mean Events Per Site	Mean Severity (%)	Mean Deficit (cm)
3 to 5	332	6.1, (2.3)	92, (3.9)	2.1, (1.6)
6 to 8	63	1.7, (0.9)	93.2, (2.9)	4.3, (2.2)
9 to 11	40	1.4, (0.7)	92.3, (2.9)	4.7, (2.3)
12 to 14	27	1.2, (0.4)	94, (2.4)	8.9, (3.5)
15 to 17	18	1.2, (0.4)	92.9, (2.4)	9.1, (4.3)
18 to 23	7	1.2, (0.4)	91.8, (3)	18.4, (9.6)
24+	7	1.0, (0)	90.9, (1.4)	25.1, (11.2)



4.9.4 Spatial distribution of drought characteristics from 1930-2010.

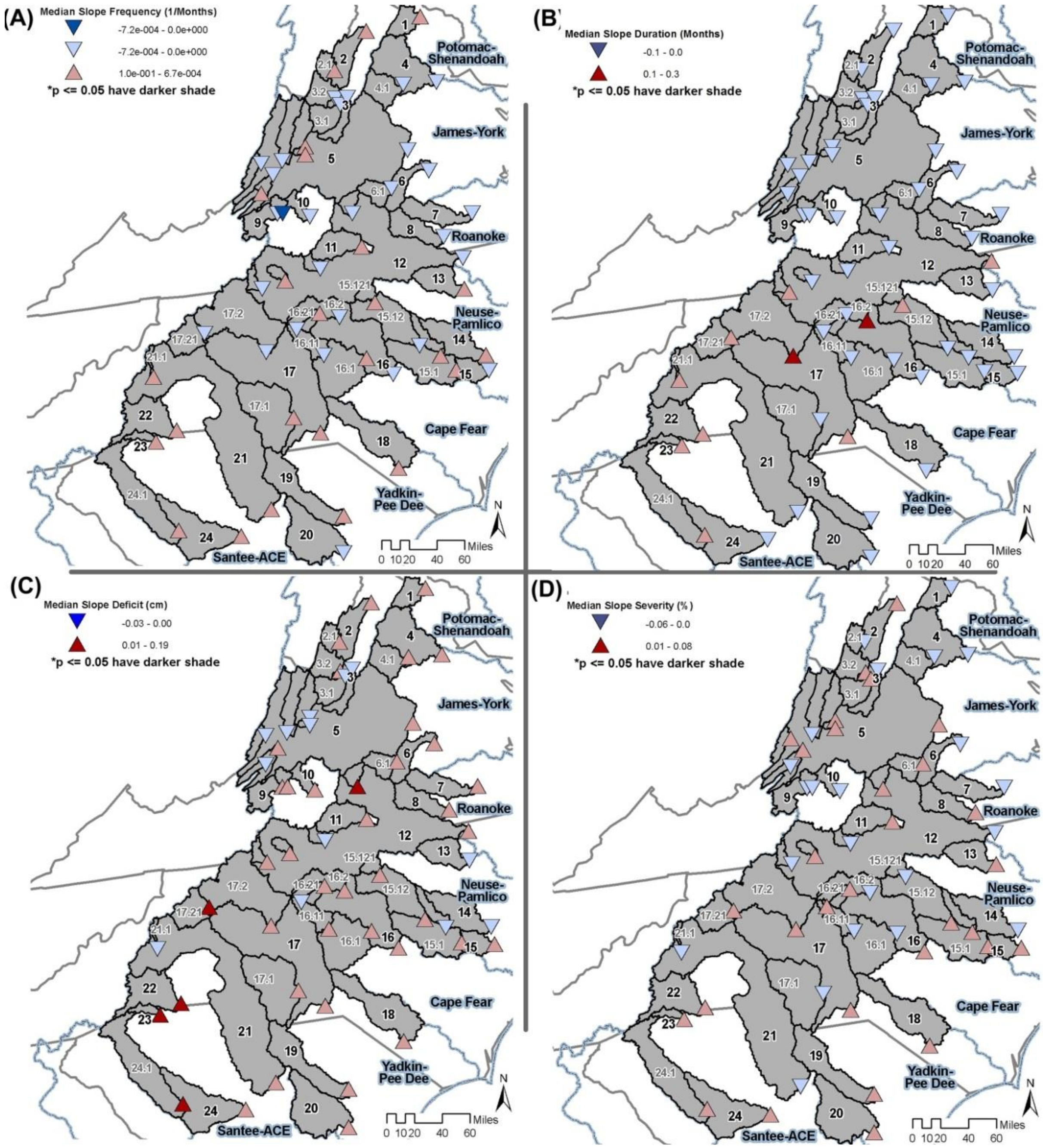


Figure 4.12: Significant trends in drought characteristics. In all panels red (blue) shade indicates increase (decrease) in drought characteristics. Dark shades are significant (p-val<=0.05) and light shades are not significant trends. (A) Frequency, (B) Duration, (C) Deficit, (D) Severity.

4.9.5 Colored Matrix of Change in Joint Probability from Mid-20th to Late-20th Century

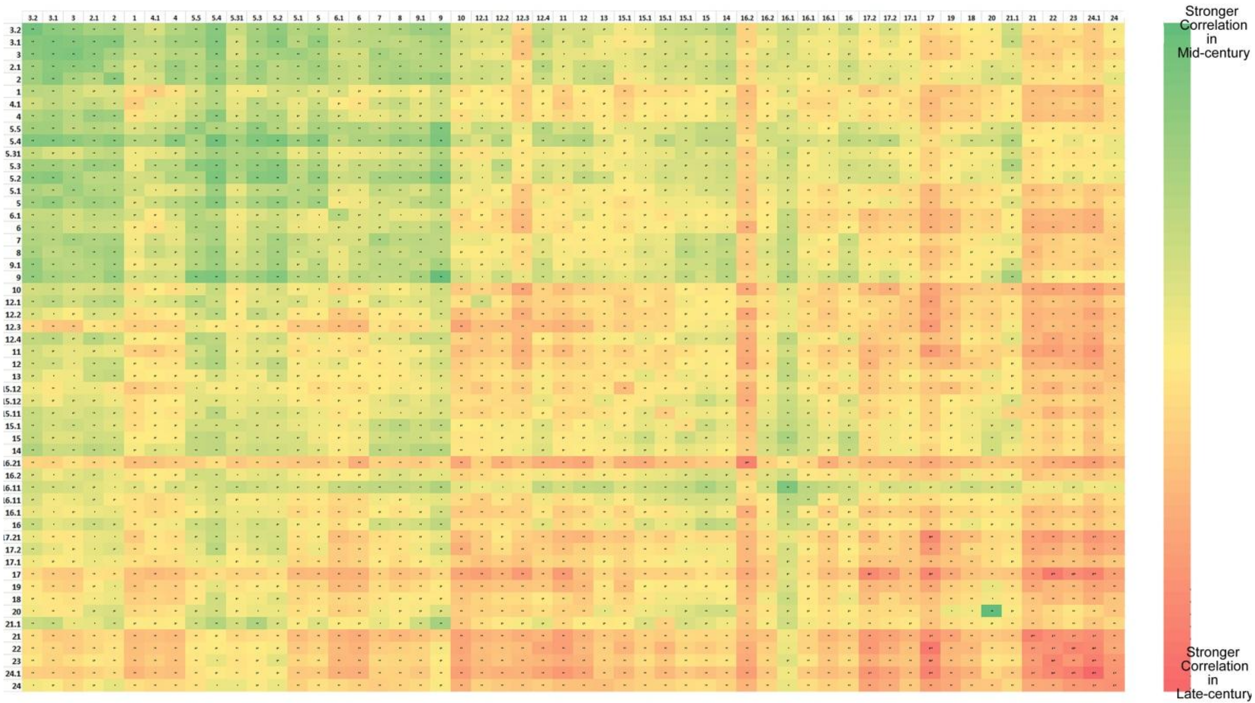


Figure 4.13: Matrix of changes in joint probability from Mid- to Late-20th Century (54 basins in numeric order). Green (red) indicates higher joint probability in Mid(Late)-20th Century.

4.10 References

Andreadis, K.M. and D.P. Lettenmaier. 2006. Trends in 20th Century Drought over the continental United States. *Geophysical Research Letters* 33 (L10403), doi: 10.1029/2006GL025711.

Andreadis, K.M., E.A. Clark, E.A., A.W. Wood, A.F. Hamlet, and D.P. Lettenmaier. 2005. Twentieth-Century Drought in the Conterminous United States. *Journal of Hydrometeorology* (6): 985-1001.

Arrigoni, A.S., M.C. Greenwood, and J.N. Moore. 2010. Relative impact of anthropogenic modifications versus climate change on the natural flow regimes of river in the Northern Rocky Mountains, United States. *Water Resources Research* 46 (W12542), doi:10.1029/2010WR009162.

Baines, P.G. and C.K. Folland. 2007. Evidence for a rapid global climate shift across the late 1960's. *Journal of Climate* 20: 2721-2744, doi: 10.1175/JCLI4177.1

Byun, H. and D.A. Wilhite. 1999. Objective quantification of drought severity and duration. *Journal of Climate* 12: 2747-1756.

Carbone, G.J. and K. Dow. 2005. Water resource management and drought forecasts in South Carolina. *Journal of the American Water Resources Association* 41 (1): 145-155

Carter, N.T., A. Abel, E.H. Buck, K. Alexander, M.L. Corn, S.M. Kaplan, and C. Brougher. 2008. Apalachicola-Chattahoochee-Flint (ACF) Drought: Federal Water Management Issues. Congressional Research Service Report for Congress. RL34326.

Dai, A., K.E. Trenberth, and T. Qian. 2004. A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5: 1117-1130.

Dracup, J.A., K. S. Lee, and E.G. Paulson, JR. 1980. On the definition of droughts. *Water Resources Research* 16 (2): 297-302.

Feldman, D.L. 2009. Preventing the repetition: Or, what Los Angeles' experience in water management can teach Atlanta about urban water disputes. *Water Resources Research* 45 (W04422), doi:10.1029/2008WR007605

Hill, T.D. and C. Posky. 2007. Suburbanization and drought: a mixed methods vulnerability assessment in rainy Massachusetts. *Environmental Hazards* 7: 291-301, doi: 10.1016/j.envhaz.2007.08.003

Hirsch, R.M. and Slack, J.R. 1984. A Nonparametric Trend Test for Seasonal Data with Serial Dependence. *Water Resources Research* 20 (6), pp. 727-732.

Karl, T.R., J.M. Melillo, and T.C. Peterson (eds). 2009. Global Climate Change Impacts in the United States. Cambridge University Press, NY. ISBN 987-0-521-14407-0.

Kauffman, G.J. and K.J. Vonck. 2011. Frequency and intensity of extreme drought in the Delaware Basin, 1600-2002. *Water Resources Research* 47 (W05521), doi: 10.1029/2009WR008821.

Konrad, C.E. III. 2002. Relationships between tropical cyclone attributes and precipitation totals: considerations of scale. *International Journal of Climatology* 22: 237-247, doi: 10.1002/joc.721

McCabe, G.J., J.L. Betancourt, S.T. Gray, M.A. Palecki, and H.G. Hidalgo. 2008. Associations of multi-decadal sea-surface temperature variability with US drought. *Quaternary International* 188: 31-40, doi:10.1016/j.quaint.2007.07.001.

McCabe, G.J. and M.A. Palecki. 2006. Multidecadal climate variability of global lands and oceans. *International Journal of Climatology* 26: 849-865.

McCabe, G.J. and D.M. Wolock. 2002. A step increase in streamflow in the conterminous United States. *Geophysical research Letters* 29 (24), 2185, doi: 10.1029/2002GL015999.

Palmer, W.C., 1965: Meteorological drought. *Research Paper No. 45*. U.S. Weather Bureau. [NOAA Library and Information Services Division, Washington, D.C. 20852]

Patterson, L.A., B. Lutz, and M.W. Doyle. (Forthcoming). Streamflow changes in the South Atlantic, USA during the Mid and Late 20th Century. *Journal of American Water Resources Association*: 25.

Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the Southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate* 22: 5021-5045, doi: 10.1175/2009JCLI2683.1

Sheffield, J., K.M. Andreadis, E.F. Wood, and D.P. Lettenmaier. 2009. Global and continental drought in the second half of the Twentieth Century: Severity-Area-Duration analysis and temporal variability of large-scale events. *Journal of Climate* 22: 1962-1981, doi: 10.1175/2008JCLI2722.1

Sheffield, J. and E.F. Wood. 2008. Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. *Journal of Climate* 21: 432-458, doi: 10.1175/2007JCLI1822.1

Sheffield, J., G. Goteti, F. Wen, and E.F. Wood. 2004. A simulated soil moisture based drought analysis for the United States. *Journal of Geophysical Research*, 109 (D24108), doi: 10.1029, 2004.JD005182.

Shiau, J.T. and H.W. Shen. 2001. Recurrence analysis of hydrologic droughts of differing severity. *Journal of Water Resources Planning and Management* 127 (1): 30-41.

Trenberth, K.E. 2011. Changes in precipitation with climate change. *Climate Research* 47: 123-138, doi: 10.3354/cr00953.

Trenberth, K.E., J.T. Overpeck, and S. Solomon. 2004. Exploring drought and its implications for the future. *EOS, Transactions of American Geophysics Union* 85 (27).

Trimble, S.W. and F.H. Weirich. 1987. Reforestation and the reduction of water yield on the Southern Piedmont since circa 1940. *Water Resources Research* 23 (3): 425-437.

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research* 47, W00J12, doi: 10.1029/2010WR010283.

Wang, A., D.P. Lettenmaier, and J. Sheffield. 2011. Soil moisture drought in China, 1950-2006. *Journal of Climate* 24: 3257-3271, doi: 10.1175/2011JCLI3733.1

Weaver, J.C.. 2005. The drought of 1998–2002 in North Carolina—Precipitation and hydrologic conditions: U.S. Geological Survey Scientific Investigations Report 2005–5053, 88 p.

Wilhite, D.A. and M. Buchanan-Smith. 2005. Drought as Hazard: Understanding the Natural and Social Context: Science, technology and management issues. CRC Press, Boca Raton, FL. ISBN-10: 0-8247-2771-1.

Wilhite, D.A. 2000. Drought: A global assessment (ed). Natural Hazards and Disasters Series, Routledge Publishers, London.

Yevjevich, V. 1967. An objective approach to definitions and investigations of continental hydrologic droughts. *Hydrology Paper 23.* Colorado State University, Fort Collins, CO.

CHAPTER 5

INTERCONNECTIONS, WATER SCARCITY AND DROUGHT[4]

5.1 Abstract

Interconnections are a means to redistribute water from a water-rich to a water-poor area. Interconnections form an important component of water infrastructure for water systems around the world, including the humid Southeast, US, by moving modest quantities of water over short distances. We assess the characteristics of 671 interconnections between 581 local government and large, private owned community water systems in North Carolina. Over the coming decades, interconnections will play an important role in water resource management by providing a viable option to increase water supply for 92% (n=62) of water systems that are projected to be water scarce (demand exceeds supply) by 2030. From a short-term emergency supply option, interconnections are most useful if one side of the connection has surplus water while the other is in drought. As a first step, we explored the probability of interconnected water systems being simultaneously in drought between 2000 and 2008, a window of time that bracketed two significant drought events. When a buying system was in drought conditions, there was a 74 to 100% probability that the selling system was also in drought. These findings show that due to the short distance (median = 11.6 km) of interconnections, most seller and a buyer combinations are often in similar drought conditions.

---

[4] Chapter 5 was co-authored with M.W. Doyle and will likely be submitted to JAWRA

5.2 Introduction

Water interconnections – the transference of water from one system to another - have been constructed throughout the world and often over great distances to transport water from a water-rich to a water-poor area. Examples include the California Aqueduct (715 km), Central Arizona Project (541 km) and Colorado River Aqueduct (389 km transfer) in the arid Western U.S. (Sabo et al., 2010), the New Valley Project (310 km transfer) and Lesotho Highlands Water Project (92 km transfer) in Africa, and the Snowy Mountains Scheme (225 km transfer) in Australia (Crase, 2007). There are also plans for new, large inter-basin transfers (movement of water between two river basins), such as the 14 transfers planned in Northern India known as the Himalayan River Component and the controversial South-North Transfer Project in China (~757 km transfer; Zhang, 2009).

Yet interconnections at smaller spatial scales between smaller water systems in humid areas are not well understood or documented. The rationale behind interconnections in humid areas is that water scarcity is often a spatial or temporal distribution problem rather than an issue of quantity. Interconnections increase the water supply portfolio of a system by increasing the effective drainage area of a water supply. This essentially creates a 'mutual fund' approach to water supply whereby the increase in spatial coverage makes it more likely that when climate is dry in one area, another area within the coverage may have more water available.

Questions arise concerning at which spatial scale are interconnections necessary to achieve water security goals. That is, is there a scale at which interconnections may not be justified from a drought mitigation standpoint because the likelihood of an adjacent basin being in drought is equally probable to the basin in search of water?

North Carolina provides an opportune case study to address these questions. The basic geography of the eastern seaboard is a line of nearly parallel drainage basins of comparable size, climate, and topography. Moreover, this region has experienced two multi-year, statewide droughts since 1998 that have resulted in the establishment of interconnections to alleviate drought induced water scarcity (LWSP, 2012). An additional factor is the geography of development with inland urban growth centers located along the Fall Line between the Piedmont and Coastal Plain (e.g. Richmond, Raleigh, Columbia). Thus, rapidly growing, major urban development is located in the headwaters or mid-reaches of the Piedmont, where there is less surface water (Palmer and Characklis, 2009) and groundwater availability (Whisnant and Holman, 2010).

In this study, we explore the potential for interconnections to alleviate long-term water scarcity and short-term drought in North Carolina. First, we build and characterize the interconnection network between water systems. Second, we used local water supply plans to examine the change in long-term supply and demand ratios between 2010 and 2060 for the CWS. Lastly, we examined the probability of interconnected systems being simultaneously in drought conditions between 2000 and 2008, a period that encompassed two significant droughts. The efficacy of redistributing water from “no-drought” systems to “in-drought” systems is limited if all systems are in-drought conditions. The statewide characterization and exploration of interconnections as a means to alleviate water scarcity is an important step toward understanding the potential for interconnections to reduce regional water system vulnerability to drought.

5.3 Snapshot of Water Resources in North Carolina

Interconnections have become an integral part of the water management infrastructure in North Carolina as they expand water portfolios by building redundancy and diversity into the system in order to reduce the risk of water scarcity. We define water scarcity as occurring when demand equals or exceeds supply. Interconnections have been used in North Carolina to address at least three drivers of water scarcity: (1) growing demand (Carbone and Dow, 2005), drought (Weaver, 2005), and groundwater depletion (Kirsch and Characklis, 2008).

5.3.1 Interconnections and Water Scarcity due to Growing Demand

Many regions along the eastern coast of the US, including North Carolina, have undergone three major economic transformations that have shaped the current state of water supply systems (Hill and Polsky, 2007). Initially, agricultural production fueled large scale deforestation through the early 1900s with a heavy reliance on groundwater or surface water irrigation (Figure 3.2C). This was followed by an industrial era from the early 1900's until the 1970's that resulted in farm abandonment, reforestation, and the construction of reservoirs (including textile mills; Figure 3.2C, Figure 3.4). During this era large industry drove water system infrastructure and resulted in the development of water treatment plants with large capacity in many small towns. The region has since been in a post-industrial economy that requires less water intensive services. As many industries have departed, small community water systems are left with excess capacity and a funding gap to maintain the water system adequately (LWSP, 2012).

North Carolina's population increased rapidly during the post-industrial era, placing greater demand on water resources. The population is projected to increase from 8.5 million in 2004 to 12 million in 2030 with water consumption increasing by 94 billion gallons per year (39% increase; Whisnant and Holman, 2010). Moreover, the largest cities and areas of high population growth in North Carolina are located in the headwaters of the Piedmont (Figure 5.1A). The result is a limited ability to substantially increase water supply storage in the midst of increasing water demand, leaving a complex mixture of private wells, small water systems with excess supply, and large water systems with limited water supply. It is already acknowledged that high growth areas in North Carolina cannot be sustained without more robust state and regional means of managing water demand, sharing water resources, and/or increasing water storage (Whisnant and Holman, 2010). Interconnections provide one avenue by sharing water resources between water rich and water poor water systems.

5.3.2 Interconnections and Water Scarcity due to Drought

There have been no significant, regional increases in hydrological drought (hereafter "drought" refers to a deficit in streamflow) in North Carolina over the last half century (Patterson, Chapter 4). However, while drought has remained constant, average monthly streamflow has decreased since the 1970s throughout much of North Carolina (Patterson et al., Forthcoming). Thus, two identical droughts (one in 1970 and one in 2010) could have very different consequences for water systems given the change in average streamflow conditions and growing water demand.

There were two statewide, multi-year droughts from 1998-2002 and 2007-2008 (Figure 5.1B) that resulted in new record lows in streamflow (Seager et al., 2009; Weaver, 2005). Several reservoirs reached record lows that compelled water utilities to take emergency action, including the installation of interconnections to alleviate drought conditions. For example, during the 2007-2008 drought, twelve new emergency interconnections were established throughout North Carolina, with seven of these interconnections attached to the Goldsboro water system in the Coastal Plains (Water Wiki, 2010).

Historically, supply expansion was the initial response to protect against drought; however, now that options to expand water supply are limited, curtailing water demand and redistributing water are more viable options (Hill and Polsky, 2007). During the 2007-2008 drought, demand management involved mandatory restrictions to reduce water consumption and many large water systems decreased their daily water use by 30 percent (Lafsky, 2007). While demand management addresses one component of scarcity, short-term water supply augmentation via emergency interconnections has been pursued to address the supply component of scarcity.

5.3.3 Interconnections and Capacity Use Areas

The Central Coastal Plain is an area where demand has exceeded the rate of aquifer recharge and resulted in groundwater depletion. Since 2000, a 15 county region in the Central Coastal Plain is under regulation to decrease water withdrawal by 30 to 75% before 2016 (Kirsch and Characklis, 2008). As a result, many groundwater systems in the CCP Capacity Use Area (CCPCUA) have started using surface water, compiling resources to form regional systems, and/or developing the infrastructure and institutional capacity for interconnections. As of 2010, the percent of interconnected water systems in the Coastal Plains of North Carolina was three times greater than the Piedmont or Mountain Region (Patterson and Eskaf, 2011).

5.3.4 Inter-basin Transfers in North Carolina

There are two primary statutes in North Carolina to govern water allocation. The first is the Water Use Act of 1967 that authorizes the designation of Capacity Use Areas, as aforementioned with regards to the Coastal Plains (Moreau and Hatch, 2008). The second is the statute governing inter-basin transfers (IBT), or the permanent movement of water from one basin (source) to another basin (receiving). IBTs typically occur when a water system extends over more than one basin or when two interconnected water systems are located in different basins. An interconnection does not have to be an inter-basin transfer and can occur between systems within the same basin.

The North Carolina General Assembly first created laws to regulate surface water IBTs exceeding 2 million gallons per day (mgd) in 1993 (G.S.§143-215.22). Regulation was put in place to enforce assessments regarding the environmental and socioeconomic impacts of transfers on the source and receiving basins. It is a state policy that priority is given to the needs of water systems located within the source basin, rather than the needs of water systems serving areas outside their source basin. In North Carolina, IBT law is applied to a mixture of sub-basins (n=38) and river basins (n=17; Figure 5.1). As of 2006, there were approximately 96 water systems serving more than 150 communities using IBTs for both withdrawals and wastewater discharge (Table 5.1; Water Wiki, 2012). With respect to drought, IBTs serve as an opportunity to obtain water from two different source basins, one of which may not be in-drought.

While IBT regulations are important for environmental and socio-economic protection, they also place some challenges on water resource management. First, IBT regulations limit access to water supply for some water systems, particularly since IBT boundaries are at the scale of the sub-basin. This is problematic for cities located in the headwaters of the Piedmont, where demand is growing beyond the capacity of local supplies (Moreau and Hatch, 2008). Second, the process of obtaining an IBT certificate is lengthy and the potential revocation of an IBT certificate can undermine the planning and development of water systems to meet rising demand (Water Wiki, 2012). These challenges created by current IBT regulations discourage the development regional water supply plans because of the difficulty and uncertainty of obtaining an IBT.

5.4 Methods

5.4.1 Data

CWS and Interconnections Data:

Water system location and information were obtained from the Environmental Finance Center (EFC) at the University of North Carolina in Chapel Hill. There were 7,008 reported water supply systems in 2009. This includes federal, state, local, and privately owned water systems of any size. The EFC identified 2,124 active community water systems (CWS; Patterson and Eskaf, 2011). A community water system is any public water system that serves 15 or more service connections or that regularly serves at least 25 year round residents (NC§130A-313). In this study, we only examined those CWS that were local government owned or were interconnected to large private/federal systems with over 300 service connections (n=581 CWS). This selection of CWS removed small, predominantly groundwater dependent sub-divisions.

A relational database of interconnections was built using DENR’s Division of Water Resources’ (DWR) Local Water Supply Plans (LWSP). LWSP were formed following the passage of the 1989 Water Supply Planning Law (G.S. 143-355) that required all local governments to submit a water supply plan every five years in order to inform state water supply plans. State plans investigate the extent to which local water supply plans are compatible. Each LWSP contains information regarding the buying system, selling system, type of interconnection, size of interconnection pipes, and the average water flow between systems during the previous year.

Interbasin Transfer Data:

Interbasin transfer information and location were obtained from NCDENR DWR (http://www.ncwater.org/Permits_and_Registration/Interbasin_Transfer/). An inter-basin transfer is an interconnection between two basins as legally defined by the state of North Carolina (38 basins; Figure 5.1A). Inter-basin transfers are regulated and require state approval, whereas interconnections are contracts between local water systems.

US Drought Monitor Data:

The U.S. Drought Monitor (USDM; http://droughtmonitor.unl.edu/monitor.html) provided weekly drought classifications throughout the US from 2000 onward. The drought monitor is a compilation of measures that blends together information from the Palmer Drought Index, Soil Moisture Model Percentiles, USGS streamflow percentiles, and Standardized Precipitation Index. The drought monitor labels drought intensity from D0 as abnormally dry (21-30% streamflow), D1 as moderate drought (11-20% streamflow), D2 as severe drought (6-10% streamflow), D3 as extreme drought (3-5% streamflow), and D4 as exceptional drought (0-2% streamflow). The method for creating USDM maps is not reproducible since maps are altered by expert opinion to reflect real world conditions. However, the USDM provides continuous coverage of drought conditions across the United States. We chose the USDM because it is widely used and provides a starting point for developing a method to explore differences in drought between CWS in the US. As with any model, there are shortcomings to using the USDM as it is not designed to depict local conditions or capture small-scale spatial variation in drought severity. We chose not to use the drought data derived in

Chapter 4 because stream gauge locations only covered a small portion of the state and basin level data does not allow spatial variation in drought severity between CWS within the same basin.

5.4.2 Creating the current interconnections network

The interconnection database built from the LWSP reported that 349 CWS had at least one interconnection (66%). The exact locations of interconnections were not known and thus were drawn between the centroids of the CWS service area. In reality, the distance between most interconnections will be shorter than portrayed in this study (Fransen, 2012) because systems will connect at the location closest to the other system (not the centroid). We calculated the number of components, which are the groups of CWS that share a physical connection (Figure 5.1; see Figure 5.2 for an example) and the number of CWS within each component. For example, one component may include 13 CWS while another component may have two CWS. Interconnections may have bi-directional flow (water can go in both directions), but many interconnections are uni-directional (one CWS sells water to another CWS). This is particularly true in mountainous areas where pumping water uphill is impractical (Patterson and Eskaf, 2011).

5.4.3 Interconnections and long-term supply and demand

LWSP provided supply and demand projections for water systems every ten years from 2010 to 2060. Five hundred twenty five CWS (90%) had information on supply and demand in 2010, 523 (90%) in 2030, and 479 (82%) in 2060. We calculated the difference (supply-demand, mgd) for each decade. Systems that purchase all of their water supply often report equal supply and demand. The results were compiled with respect to interconnection status: buying, selling, or not connected.

Water demand is often greatest during summer months, when precipitation and streamflow are at their lowest. Demand peaks because of lawn irrigation, power plant needs for air conditioning, and agricultural irrigators (Whisnant and Holman, 2010). We looked at two case studies of the relationship between water supply and demand during average streamflow and drought conditions. This example highlights the different impacts the same drought can have on a water system given pre-existing conditions (i.e. supply-demand and geographic location). We compared the average monthly streamflow at Flat River, NC (USGS gauge 2085500) with water withdrawals by the City of Durham from Lake Michie (~7 km downstream) in 2010. We then applied this comparison during the years 2002 and 2007, when this region was in extreme drought. The same procedure was repeated for the Yadkin River, NC (USGS Gauge 2112000) with water withdrawals from the City of Wilkesboro (within 1 mile of the gauge). Both gauges and cities were selected because they are located in the headwaters and the gauge and water supply are located near one another.

5.4.4 Interconnections and drought

CWS centroids were intersected with the weekly USDM values to obtain the drought status for each CWS through time. The data were extracted and placed into a matrix that contained CWS drought status through time for each component (group of physically connected CWS; Figure 5.2). We created a binary matrix with each week being either 0 (no-drought) or 1 (in-drought) for the remainder of the calculations. This does not account for differences in the severity of drought between CWS, but merely the presence or absence of drought. This initial method simply looks at interconnections and drought, without taking into consideration water system characteristics or water scarcity. Future work would incorporate both drought severity and water system characteristics in order to accurately assess the capacity of the interconnection network to alleviate drought-induced water scarcity.

For each component, we calculated the percent of CWS in-drought at each time step and averaged those values to get an overall drought probability for the component. Drought probability is the percent of time a CWS or Component was in drought conditions from 2000-2008. The southeast USA is not known for regional, multi-year droughts (Andreadis et al., 2005); however, there were two statewide, multi-year droughts in this region during the time when USDM data were available. We realize the limited time-frame for assessing CWS and USDM drought data may bias results. However, we can observe the probability for interconnections to alleviate drought during these two events.

For each time step when one CWS within a component was classified as in-drought, we calculated the conditional probability of the other CWS within the component also being in-drought. We repeated this step for components to determine the conditional probability of different components simultaneously being in drought conditions. A paired t-test was used to assess significant differences in drought conditions between adjacent components. Adjacent components were considered those components located within 11.6 km (8 miles) from another component. This is the median distance between currently interconnected CWS in North Carolina and a reasonable distance to consider new interconnections. If there is a significant difference in drought probabilities, then these components may benefit from being interconnected to form a larger component that has proven to be spatially different from drought patterns over the last decade.

For each component, we multiplied the drought probability and the conditional probability to get the joint probability, which is the probability of CWS within a component being simultaneously in drought from 2000-2008.

Lastly, we applied the above methods to individual water sales between sellers and buyers. First, we calculated the probability of buyers being in drought from 2000 to 2008 (P(B)), where P is the probability and B is the buying system. Then we calculated the conditional probability of a seller being in drought given a buyer was in drought conditions (P(S|B)), where S is the selling system. Lastly, we calculated the joint probability of both buyer and seller under drought conditions from 2000 to 2008 (P(B)*P(S|B); Figure 5.2).

5.5 Results

5.5.1 Characteristics of CWS interconnections in North Carolina

There were 671 interconnections between the 581 CWS represented in this study, including emergency and regular contracts. There were 400 (69%) buying systems, 282 (49%) selling systems, and 106 (18%) with no interconnections. CWS may both buy and sell water. The CWS with the most interconnections were county systems located near Raleigh (in Component 0) along the Fall Line (shift from the Piedmont to the Coastal Plain; Harnett County with 12 water sales and 8 purchases and Johnston County with 12 water sales and 6 purchases). There were 43 components (physically connected groups of CWS). The largest component (Component 0) consisted of 174 CWS. This was followed by Component 1 with 57 CWS. There were 19 components that consisted of paired CWS (only one connection).

5.5.2 Water scarcity and interconnections for long-term supply and demand

Water supply was projected to increase for 125 CWS (25%) by 2030, whereas water demand was projected to increase for 472 CWS (94%). Sixty-five CWS anticipated a decrease in water supply by 2030. CWS that reported decreasing water supply were predominantly groundwater systems located in the CCPCUA (e.g. Beaufort, Jonesville, and New Bern; LWSP, 2012).

Eight percent of CWS in 2010 were characterized as water scarce (demand equaled or exceeded supply). Seven percent of these water scarce CWS were purchase systems (Table 5.2; Figure 5.4), some of which were open contracts whereby water supply was equivalent to demand. Three percent of water scarce CWS only sold water or had no interconnections. The average population size for water scarce CWS was 2,442 with the largest water scarce CWS having a population of nearly 20,000 (North Brunswick Sanitary District; both buys and sells water). By 2030, thirteen percent of CWS projected water scarcity (Table 5.2; Figure 5.4). Twelve percent of water scarce systems were buyers, 6% sellers, and 1% not connected. The average population served by water scarce CWS in 2030 increased to 7,000 (2010 population). The two largest CWS with demand exceeding supply were Cary (149,000, 2010 population) and Cleveland County (57,000, 2010 population). Both of these CWS were interconnected to CWS with excess supply in 2030.

The likelihood of CWS having an interconnection increases with CWS size (Patterson and Eskaf, 2011). There are 13 CWS serving over 100,000 people in 2010 and all have an interconnection to sell water. Seven of these systems predict water scarce conditions by 2060, including the two largest cities in North Carolina (Charlotte and Raleigh). By 2060, LWSPs projected that nearly one quarter of CWS will be water scarce (Figure not shown). Eight percent of the 2060 water scarce CWS were currently not buying water.

5.5.3 Case study – context matters for water scarcity triggered by drought

Peak water withdrawals often coincide with minimum streamflow, and we found that Durham's water withdrawals at Lake Michie (~385 km^2 drainage area) were equivalent to 5% of average flows in the spring and winter and up to 21% of average streamflow during summer and fall (Figure 5.5). Water withdrawals exceeded streamflow for several months during the 2002 and 2007 droughts by orders of magnitude. Streams with adequate flow to meet demand during normal conditions are not always capable of meeting demand during drought. Durham has reservoirs on both Flat River (Lake Michie) and Little River (Little River Reservoir) to store excess water in case of drought. However, the combined storage holds less than a year of water supply (number of days varies depending on current demand). During the 2007 drought Durham sought additional water supply from a nearby quarry as their reservoirs reached record lows.

In contrast, Wilkesboro's water withdrawals from the Yadkin River (~1300 km^2 drainage area) were equivalent to 0.4 to 0.8% of average streamflow. During the two drought events, withdrawals rose to 2.4% of available streamflow (Figure 5.5). Wilkesboro has approximately half the demand of

Durham and three times the drainage area for water supply purposes; thus, Wilkesboro's demand never exceeded raw streamflow capacity. The contrast between the circumstances these two utilities faced with respect to their available water supply during regional drought highlights that interconnections can still be of value even if both utilities are in the same drought event. This is particularly true when the impact of drought is exacerbated by high water demand relative to available water supply (e.g. Durham). Setting aside supply and demand ratios, what is the prognosis for these interconnections to extend beyond the spatial extent of drought?

5.5.4 Interconnections and Drought

Two multi-year, state-wide droughts occurred in North Carolina between 2000 and 2008 (Figure 5.6; see Figure 5.2 for assistance to interpret figure). All CWS were simultaneously in drought conditions for 51 weeks (11% of the time). The greatest variation within a component (i.e., not all CWS are in drought conditions) occurred at the onset and termination of drought events. The average standard deviation for CWS in drought conditions within a component ranged from 0% (Components with 2 to 7 CWS) to 11% in the largest component (174 CWS). There was greater variation between components than within components (average stdev: 19%, range: 0-50%). For example, the year 2000 was substantially wetter for Component 0 than for Component 1, but the drought condition within each component was similar in 2000 (Figure 5.6). Higher variation in drought status by CWS within a component, and between components, indicates larger differences in drought conditions and increased likelihood in the ability for interconnections to have different drought circumstances.

Drought within a component

Components (groups of physically interconnected CWS) spent an average of 33±11% of the time period in drought (range: 17% in Component 30, Coastal Plain to 50% in Component 12, Mountain Region). Drought probability, or the probability of a component being in drought, is dependent on the location and orientation of both the component and drought.

The conditional probability of CWS within a component being simultaneously in drought ranged from 61% (Component 0 – the largest component) to 100% (11 components with 2 to 4 CWS; Figure 5.7). The conditional probability decreased as component size increased. This is a simplified assessment as the location, orientation, and degree of separation between CWS within a component are important contributing factors (Figure 5.7B). For example, Component 0 extends throughout the state in a N-S direction and has a similar extension in the E-W direction; whereas, Component 1 is located W of Component 0 and has a NW-SE orientation with little NE-SW spread between CWS within the component.

The joint probability of CWS being in-drought within a component was similar to the drought probability (average 31±11%). Joint probability accounts for the spatial orientation of the component in relation to the spatial orientation of recent drought events. Since the average conditional probability was 95%, there was little differentiation between joint probability and drought probability.

Drought between components

All CWS were in drought conditions for 51 weeks (11% of the time) between 2000 and 2008 (446 weeks; Figure 5.8). During these weeks there was no variation between components because all components were in drought. However, there were 303 additional weeks (68% of the time) when drought conditions varied between components. If drought conditions varied significantly between components over time and these components were located nearby, then they may be ideal candidates for future interconnections.

Existing interconnections had a median distance of 11.6 km (8 miles). The distribution was right skewed with fewer interconnections at greater distances (80% were within 22 km; Figure 5.9A). Assuming new interconnections are more feasible at shorter distances; we selected pairs of components located within the median distance (n=19). Paired t-test indicated significant differences in drought status between 14 of the 19 options (p<=0.05). Seven of the significant pairs were with Component 0, which had a lower conditional probability than all other components (Figure 5.7). Significantly linked components are shown in Figure 5.9B.

Drought Probabilities Between Buyers and Sellers

The probability of a CWS being in drought ranged from 18 to 63% (average 34±10%; Figure 5.10A) with an East to West spatial orientation, respectively. The conditional probability of a seller being in-drought if the buyer was in-drought was greater than 74% for all interconnections (Figure 5.10B). This means that at least 74% of the time a buying CWS was in-drought, the selling CWS was also in-drought. The average conditional probability was much higher at 98±3%. The conditional probability decreased as the length between interconnections increased (Table 5.3).

The joint probability for CWS had a similar spatial pattern to the probability of CWS being in-drought during this time period (average 33±10%; Figure 5.10C) due to the high conditional probability. Thus, Coastal Plain interconnections had less than a 25% probability of being in-drought from 2000-2008. In contrast, interconnections in the Mountain Region had a 46-53% probability of being in-drought during that same time period.

5.6 Discussion

5.6.1 Interconnections and Drought

We found that when a buying system was in drought conditions, there was an average probability of 98% that the selling system was also in drought. The conditional probability slowly decreased as the distance between interconnections increased (Figure 5.10; Table 5.3). Thus, from a binary view of drought, it appears that these smaller and shorter interconnections often shared the same extreme conditions (Figure 5.9A). But there were also implications if wheeling occurred; wheeling is the movement of water from a seller through several interconnections (or ‘virtual’ water movement through interconnections), it could reduce the conditional probability (Figure 5.7). This is particularly true for larger components (conditional probability = 61-82% for components with 26 or more CWS). As a component becomes more spatially expansive there is greater probability for water distribution to exceed drought coverage, since interconnections essentially expand the spatial scale of water supply acquisition (van der Zaag and Gupta, 2008).

The variation in drought status between interconnected systems was greatest toward the onset and termination of drought (Figure 5.6 and Figure 5.8). Historically, inter-basin transfers, and interconnections in general, have been used to mitigate the impact of short-term droughts (<6 months); however, the ability to maintain supply during longer droughts is questionable (Pulwarty et al., 2005). Almost three quarters (71%) of drought events in the South Atlantic have historically been less than 6 months and only 7% of drought events exceeded one year (Patterson, Chapter 4). In the case of shorter droughts, the onset and termination period are nearly equivalent to drought duration. However, the onset and termination of droughts account for a smaller portion of the drought event as the duration increases. In this study, we assessed the conditional probability of drought status for interconnections during two statewide, multi-year drought events (Weaver, 2005), which poses the greatest challenge to the vitality of interconnections for drought mitigation during some of the most adverse conditions experienced in this region since the Dust Bowl.

5.6.2 Case Studies of drought exacerbating water scarcity

Once all CWS in a component are in-drought the ability for interconnections to alleviate drought induced water scarcity becomes increasingly dependent on drought severity, the excess water supply available at the selling CWS, and water demand. The case studies provided an ideal example of how two differently situated CWS experienced the same drought and the importance of future work to incorporate drought and water system characteristics into the model (Figure 5.5). The length and severity of the 2007 drought was such that it approached the capacity for Durham's reservoir to continue supplying water and it required the city to seek additional water supply from a nearby quarry. During these drought events, water demand was approximately 65% of normally available water supply (13.6 mgd difference). By 2030, Durham projected water demand would be 88% of normally available water supply (4.9 mgd difference). This implies that if the status quo is maintained, a drought similar to the one that occurred in 2007-2008 would have an even more detrimental impact on the city's water resources in 2030.

In contrast, Wilkesboro did not experience the same water shortages that Durham faced due to excess supply relative to demand (currently 26% of normally available water supply; 13.8 mgd difference) and the location of the city is farther downstream, where rivers are naturally larger. Thus, the presence or absence of drought does not determine water scarcity. This is why some CWS successfully established interconnections to other CWS in similar drought conditions that still had excess water supply. For example, Salemburg (in the Piedmont/Mountain Region) established supply connections with China Grove, Kannapolis, Landis, and Statesville in response to the 2002 drought (LWSP, 2012) even though all of these CWS were simultaneously under drought conditions.

5.6.3 Supply and Demand

CWS make decisions that impact either supply or demand for either the long-term or short-term. Here we will look at long-term supply and demand pressures facing CWS. Population has become increasingly concentrated as people move from rural areas to cities (Mitchell et al., 2006). The result has been increased water demand in cities that have already developed their water supply infrastructure and have limited options for gaining access to new, large-scale water supply. In effect, these growing areas are required to expand water infrastructure to accommodate growth without equivalent options of increasing water supply, and the result can be chronic water scarcity (Hill and Polsky, 2007).

North Carolina served as our case study for the long-term challenges of managing growing water demand with limited options for augmenting water supply via reservoirs (Figure 5.4). Demand was projected to increase in 94% of CWS while 25% of CWS reported a corresponding increase in water supply. Increases in water supply can arise via increased water treatment plant capacity, ending current sales contracts, new purchase contracts, new groundwater wells, and building new water treatment plants (LWSP, 2012). One example of interconnections being utilized expressly for the purpose of increasing normally available water supply was the development of the Piedmont Triad Regional Water Authority which began operation in October 2010 (the inter-basin transfer was approved in 1991) to supply wholesale water to six communities.

In the Coastal Plain, 65 CWS reported a decline in long-term water supply due to groundwater depletion and regulation from the Central Coastal Plain Capacity Use Area (CCPCUA) to reduce water withdrawals. Many of the impacted CWS are turning toward forming regional water authorities and/or establishing interconnections to surface water systems (LWSP, 2012). Interconnections are an attractive idea for this region as population and industry have declined in recent years, particularly in small, rural coastal towns. Towns with declining populations and industries often have excess and under-utilized water supply and plant capacity that could be accessed via interconnections.

Interconnections will likely play an increasingly important role as demand approaches or exceeds supply for CWS that lack viable infrastructure expansion options (Figure 5.4). Building the network of interconnections was an important first step to better understanding how water is redistributed between CWS across the state (and average of 285 mgd was transferred in 2010) and the impact of interconnections on long-term water planning. North Carolina's developing water allocation policy is focused on understanding where and when the water budget is likely to be out of balance (i.e. when does demand exceed supply; Whisnant and Holman, 2010). The existing network of water transfers seems to be a viable option for augmenting supply to water scarce CWS in 2030. Only one component (Component 30 – with two CWS) has a situation where both CWS will be water scarce in 2030 (Figure 5.4). The remaining components have CWS with excess water supply physically connected to water scarce CWS. One percent of water scarce CWS in 2030 currently have no interconnections available.

5.6.4 Inter-basin Transfers and Implications

Inter-basin transfers (IBT) have been used to mitigate water scarcity and may play an increasingly important role in drought alleviation. As the global temperature continues to warm, local and regional changes in precipitation patterns due to slight shifts in storm tracks may make some regions wetter and some, often nearby, drier (Trenberth, 2011). A key question to continue pursuing is working to determine the critical distance (and direction) in which interconnections have a low probability of simultaneously being in similar drought conditions given historic drought patterns.

In North Carolina, there are provisions for emergency inter-basin transfers for less than six months, after which the emergency contract must be renewed. This is a suitable solution for approximately ¾ of droughts experienced in this region (Patterson, Chapter 3). The regulation of IBTs is important to protect the interest of source basins and those communities located downstream of transfers (Carter et al., 2008). However, these regulations are not specific regarding water allocation, priorities during emergency conditions, or building flexibility into the decision-making process. The result is a hindrance in the ability for proactive regional water resources management planning that is exacerbated by the difficulty in obtaining an IBT contract and uncertainty of its continual renewal. The CCPCUA is one of the few regions where regionalization and interconnection between systems is actively promoted in an effort to reduce groundwater depletion while meeting the demands of these water systems in an area without a lot of financial advantages. Water allocation rules are in the process of being developed and legalized in the Southeast and now it an opportune time to assess the statewide condition of water infrastructure and their performance under normal and adverse circumstances.

5.7 Policy Implications

"Today's policy choices become tomorrow's policy constraints" (Crase, 2007) and today's policies are being formed with respect to water scarcity in the Southeast, US. Water management systems have traditionally been designed based on the assumption of stationarity; whereby, the mean and variability of a hydrologic time series do not change over time (NRC, 2011). In other words, our current water resources infrastructure was designed to accommodate a stationary hydrologic system (Stakhiv, 2011). Unfortunately, water system tend to be stationary than hydrologic systems, and are therefore lack the flexibility to adapt well to long-term and short-term changes in surface water availability. High aversion to risk makes it difficult for water systems to change until the system is clearly not functioning, which is often during or shortly following an emergency. In addition, the ability for water systems to adapt is constrained by (1) institutional arrangements such as water laws, regulations, institutions, local politics, etc.; (2) fragmented water decision-making between multiple spatial and temporal scales; (3) the inflexibility of pre-existing infrastructure; (4) large uncertainty in future climate conditions (Lemos, 2008). All of these components contribute toward an inflexible water management system that is resistant to change even as surrounding conditions are changing.

Regardless of the cause, it is important that water systems learn how to increase their ability to respond to chronic water scarcity. One viable option to approach water scarcity is the strategic establishment of interconnections between water systems to diversify their water supply portfolio (Palmer and Characklis, 2009) and increase the overall ability of a region to redistribute water (Stakhiv, 2011).

5.7.1 North Carolina Specific Policy Implications

North Carolina has progressively moved toward institutional changes in how water resources are managed. It began with the passage of the Water Supply Planning Law in 1989 that required LWSP to be developed and submitted to the state in order to assess compatibilities between CWS. The Water Withdrawal and Transfers Registration Law (G.S. 143-215.22H) required the registration of any withdrawals or transfers exceeding 1 mgd, which laid the foundation for future development of allocation regulations. The Regulation of Surface Water Transfers Act (G.S. 143.215-22I) was designed to regulate transfers between river basins (ITB) exceeding 2 mgd in order to protect environmental and sociopolitical interests in the source river basin. This was followed by the Water Conservation and Reuse Act (Session Law 2002-167) that mandated CWS to develop and promote water systems capacity to take short-term water conservation measures during emergencies, such as drought and long-term increases in water-use efficiency. The 2008 Drought Legislation (SL 2008-143) preconditioned the need for water systems to have financially sustainable rates that promoted water conservation in order to receive state funding for water infrastructure. The Water Resource Policy Act of 2009 (SB 907) began to address the issue of ownership and water rights with the goal for the state to become more proactive in water resource planning. Other regulations promoting a shift toward intentionally managing water supply include the Capacity Use Act, Roanoke River Basin Water Allocation Law, and the Improve River Basin Modeling Act.

The window of opportunity to renovate water resource management in North Carolina is currently in place, as evident by the rapid succession of water regulations over the last few decades. Much of this legislative change was driven by severe drought events that produced region-wide water scarcity (McLaughlin, 2010). However, some of these regulations appear to be contradictory to overarching goals. For example, the Water Resource Policy Act strives to undertake basin- and state-wide planning. Yet the process of certifying ITBs is constraining the development of regional water plans to interconnect water systems with excess supply and those systems facing scarcity (Water Wiki, 2012). It is essential to regulate ITBs, but the regulations need to encourage regional planning, especially if there are no regulations that curtail growth in demand from exceeding local water supply capacity. Recently, there has been growing interest in limiting or removing IBT policies (McLaughlin, 2010), particularly since some utilities already rely on IBTs to meet demand. This problem is exacerbated by drought conditions.

Water scarcity has not been the norm for North Carolina. The relatively recent prevalence of water scarcity in major cities has led to the near simultaneous pursuit of both supply and demand side management (Feldman 2009). However, as demand continues to increase with population, it is essential for North Carolina to realize that water conservation is becoming necessary at all times, not just during drought. Several utilities have started mandatory water conservation during summer months to reduce peak demands. Droughts have been a catalyst for policy change; however, the pressures of growing water demand would eventually require increased regulatory control over water allocation. Changing water management policies is challenging work. Future scenarios indicate water shortages in major cities such as Raleigh and Durham by 2050. While challenging, it is far better to work toward a new institutional framework for water allocation now and test them with short-term emergency conditions such as drought. The opportunity of developing successful water allocation policies now could avoid entering into long-term, sustained water scarcity that would occur as demand surpasses the sustainable yield of our river basins.

5.8 Tables

Table 5.1: Selection of inter-basin transfers averaging 5 mgd or more in 2010 (source: NCDENR, 2012).

Utility	Source Basin	Receiving Basin	Amount (mgd)
Albemarle	Yadkin (18-1)	Rocky (18-4)	7
Asheboro	Uwharrie (18-3)	Deep (02-2)	5
Cary/Apex/Mrsvl/RTP	Haw (02-1)	Neuse (10-1)	24
Charlotte-Mecklenburg	Catawba (03-1)	Rocky (18-4)	33
Concord-Kannapolis	Catawba (03-1)	Rocky (18-4)	10
Concord-Kannapolis	Catawba (03-1)	Yadkin (18-1)	10
Durham	Neuse (10-1)	Cape Fear (02-3)	14
Gastonia	South Fork Catawba (03-2)	Catawba (03-1)	11
Greenville Utilities	Tar (15-1)	Contentnea Creek (10-2)	8
Hickory	Catawba (03-1)	South Fork Catawba (03-2)	5
High Point	Deep (02-2)	Yadkin (18-1)	7
Piedmont Triad	Deep (02-2)	Haw (02-1)	31
Piedmont Triad	Deep (02-2)	Yadkin (18-1)	
Statesville	Yadkin (18-1)	South Yadkin (18-2)	5
Wilmington	Cape Fear (02-3)	Northeast Cape Fear (02-5)	5

Table 5.2: Percent of CWS where demand equaled or exceeds supply

Year	2010	2020	2030	2040	2050	2060
All Systems	8%	10%	13%	16%	19%	24%
Buyers	7%	9%	12%	13%	16%	19%
Sellers	2%	3%	6%	7%	9%	11%
Not Connected	1%	1%	1%	2%	2%	2%
Number of reporting CWS	526	525	523	504	499	479

Table 5.3: Conditional probability and interconnection length.

Distance (km)	Sites	Average Conditional Probability
0 to 4	62	99.5% ± 1.0%
5 to 9	160	99.1% ± 1.7%
10 to 14	148	98.6% ± 1.9%
15 to 19	104	97.9% ± 2.8%
20 to 24	72	97.1% ± 3.2%
25 to 29	55	96.7% ± 3.5%
30+	57	95.3% ± 5.6%

5.9 Figures

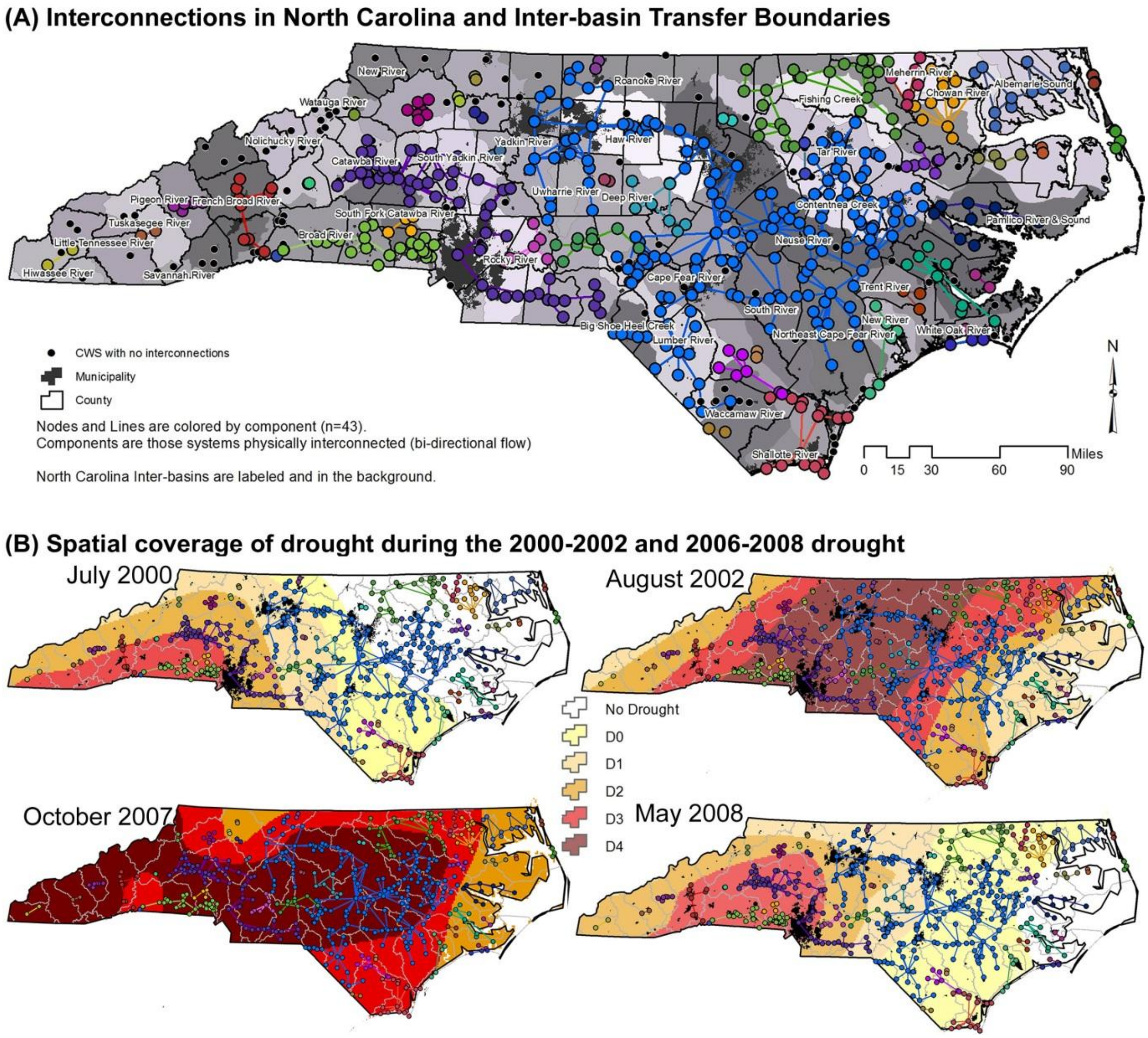
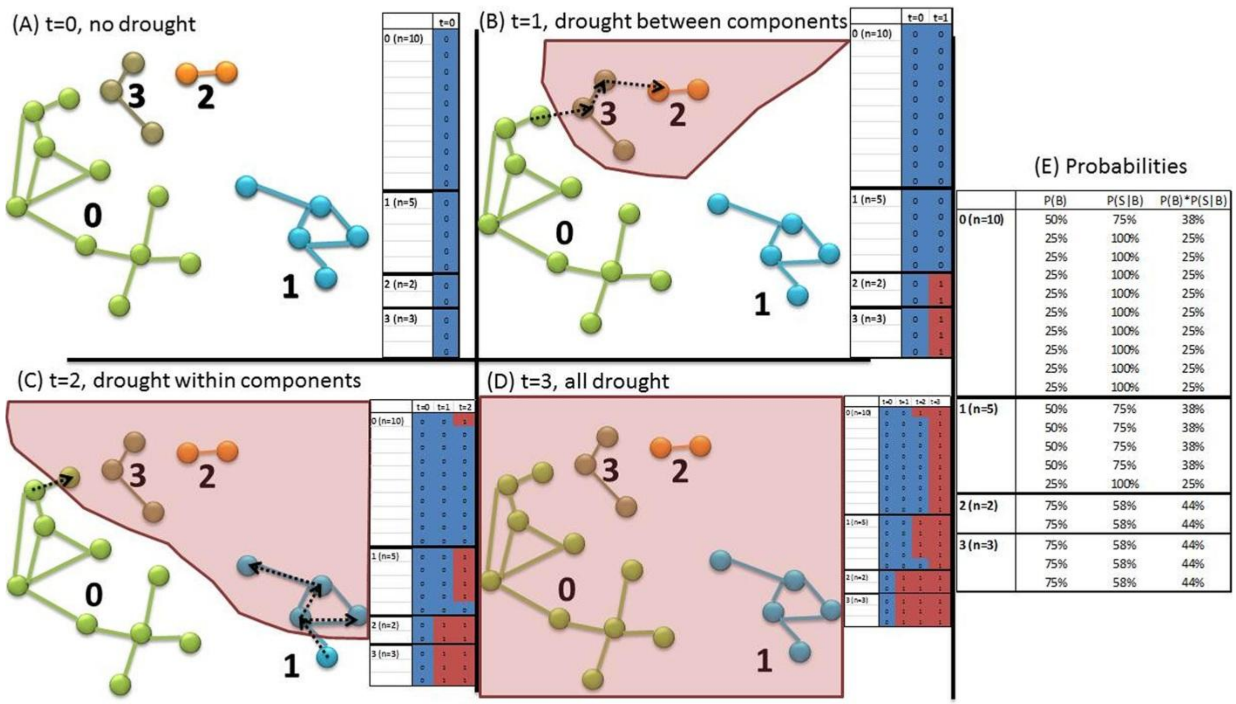


Figure 5.1: CWS and Interconnections included in this study for North Carolina. (A) 581 CWS and their interconnections. Colors represent groups of CWS that are physically connected (termed components). (B) Interconnections and drought conditions. July 2000 is the beginning stages of state-wide drought. August 2002 and October 2007 were both times of statewide drought. May 2008 is in the termination stages of drought.



	P(B)	P(S|B)	P(B)*P(S|B)
0 (n=10)	50%	75%	38%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
	25%	100%	25%
1 (n=5)	50%	75%	38%
	50%	75%	38%
	50%	75%	38%
	50%	75%	38%
	25%	100%	25%
2 (n=2)	75%	58%	44%
	75%	58%	44%
3 (n=3)	75%	58%	44%
	75%	58%	44%
	75%	58%	44%

Figure 5.2: Interconnections and drought. Four components (groups of physically connected systems) are shown. Component 0 has 10 CWS, Component 1 has 5 CWS, Component 2 has 2 CWS, Component 3 has 3 CWS. The table on the right side of each section shows the drought status during that and preceding time steps (blue=no drought, red = in drought). (A) No drought. (B) Drought conditions exist for Component 2 and 3, but not Component 0 and 1. Component 0 and 3 in this example are close enough that an interconnection could be established to alleviate drought conditions (dotted arrows). (C) Drought expands and covers parts of Component 0 and 1. There are CWS within each component that are not in drought condition and may be able to redistribute water depending on system characteristics. (D) All systems are in drought conditions. (E) Probabilities are calculated for each CWS within each component during this hypothetical 4 month time series.

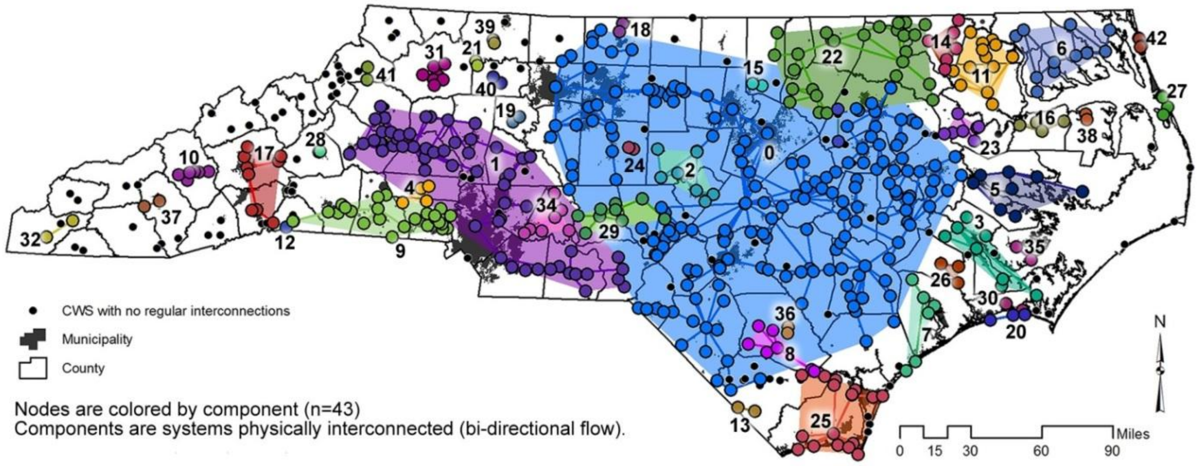


Figure 5.3: Interconnection components. The largest component (0) contains 174 CWS (blue). This is followed by Component 1 with 57 CWS (dark purple). Component numbers were randomly assigned.

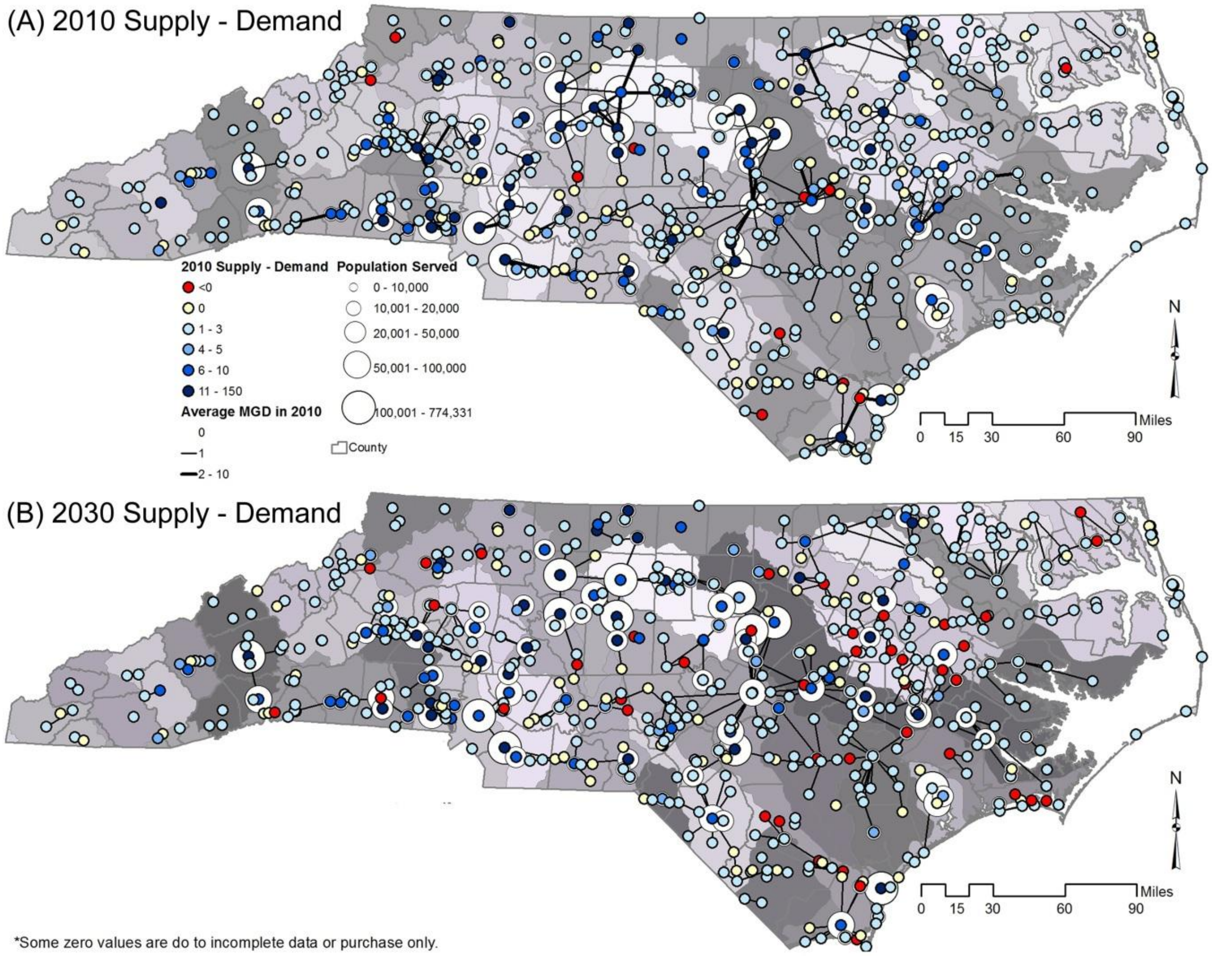


Figure 5.4: Difference between supply and demand for reporting CWS. The population served by each CWS in 2010 is overlayed by the difference between supply and demand. Red values indicate demand exceeds supply. Yellow values indicate CWS where demand=supply. Shades of blue indicate levels of excess supply. The amount of water transferred between systems in 2010 are shown (emergency transfers not activated in 2010 are not shown in this map).

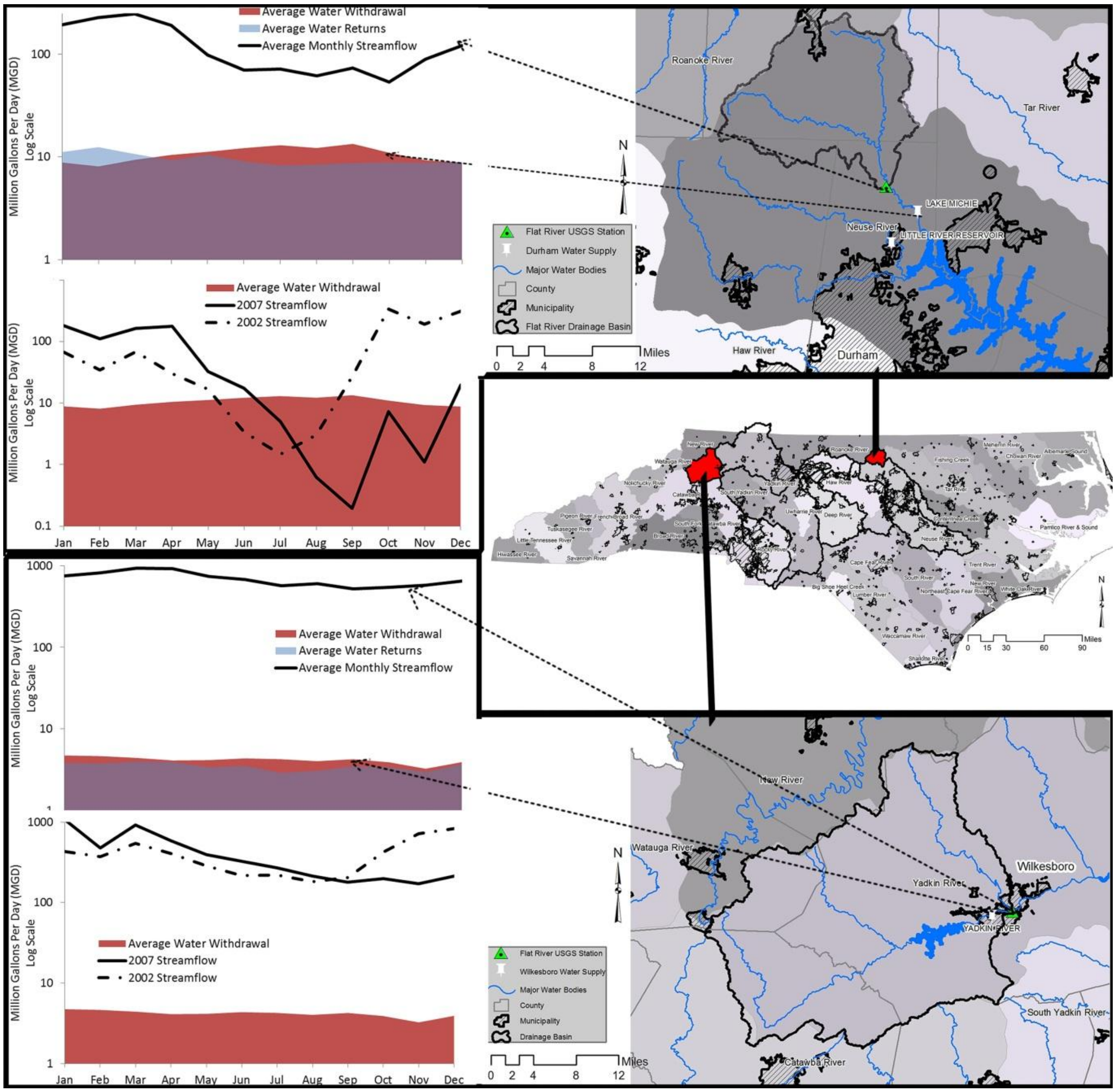


Figure 5.5: (Top) Comparison of water withdrawals and streamflow along the Flat River, NC. (Bottom) Comparison of water withdrawals and streamflow along the Yadkin River, NC. In both figures, the top left panel shows average withdrawals and discharges in 2010 compared to average streamflow from 1930-2010. The bottom left shows the average withdrawals in 2010 compared to streamflow during two drought years (2002 and 2007). The y-axis is log-scaled. The right panel shows the geographic location of the stream gauge and intake source for the city.

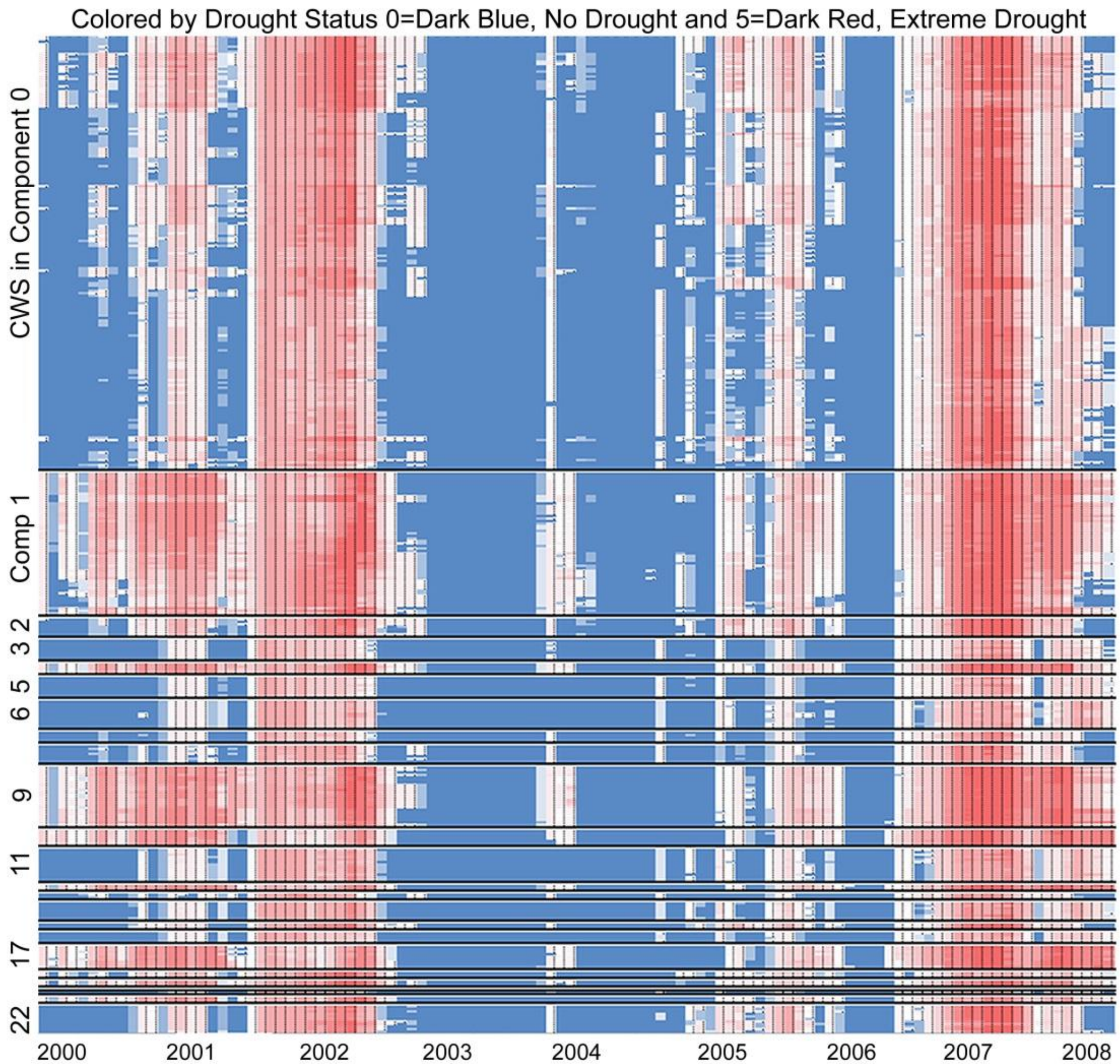


Figure 5.6: Matrix of USDM drought index for each CWS by component. Shades of blue indicate no drought. Increasingly dark shades of red indicate increasing dryness.

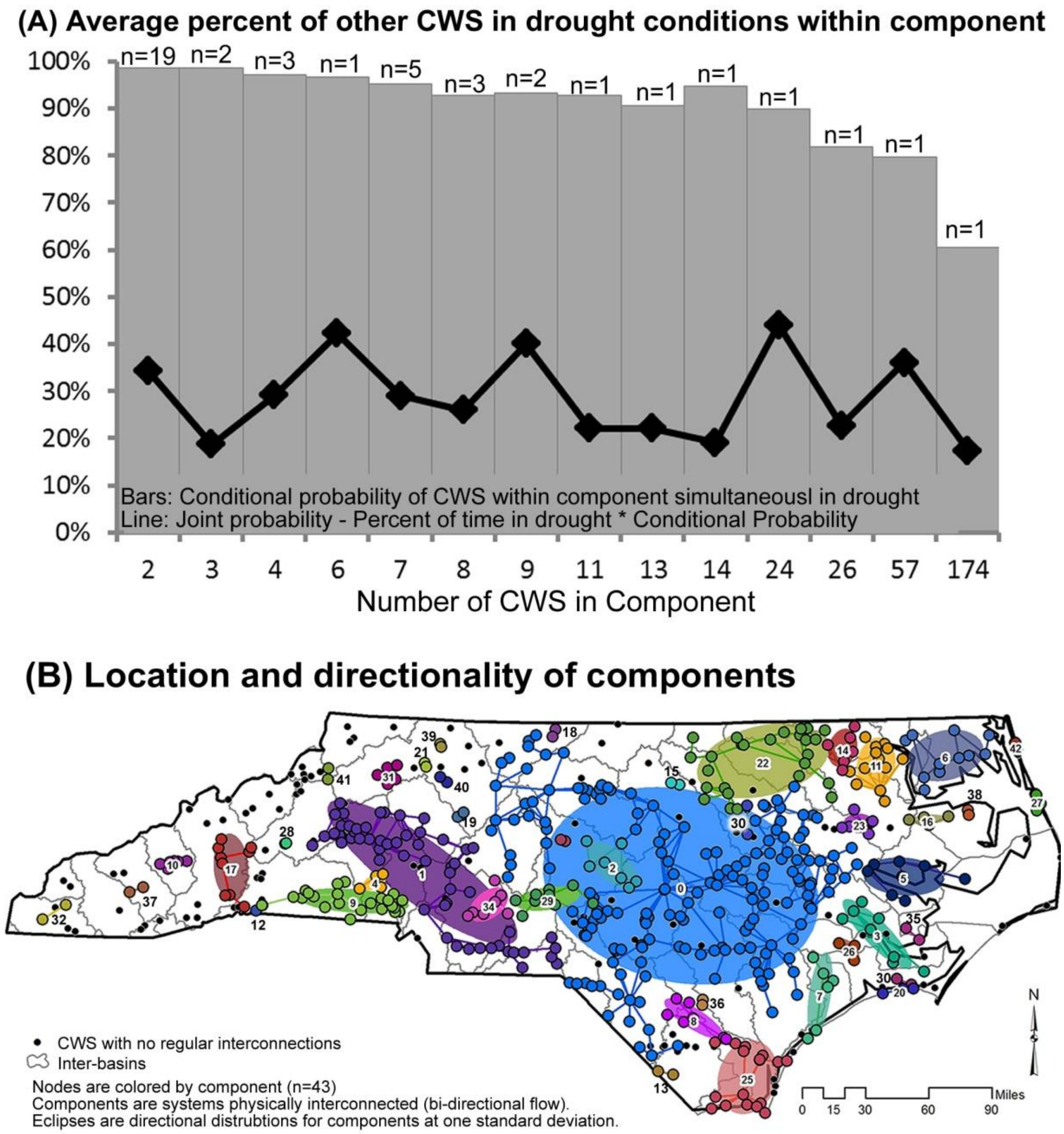


Figure 5.7: Percent of CWS in drought based on component size. (A) Average percent of CWS in drought (number of components in sample decreases as component size increases). (B) The spatial breadth and orientation of CWS components in North Carolina.

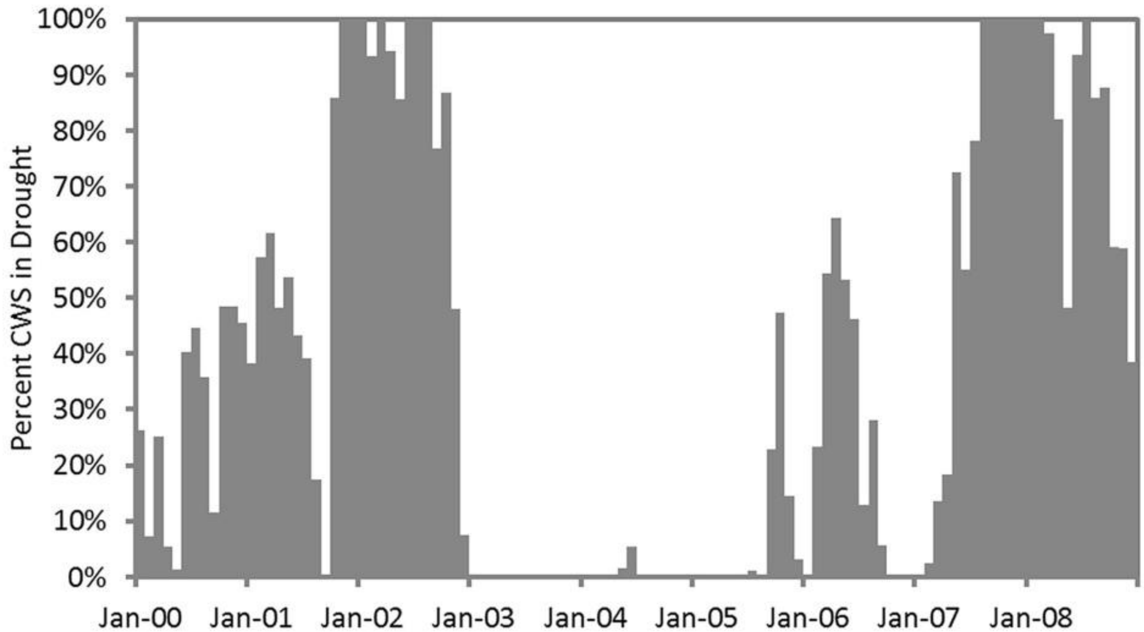


Figure 5.8: Average percent of CWS within each component (n=43) in drought condition from 2000-2008.

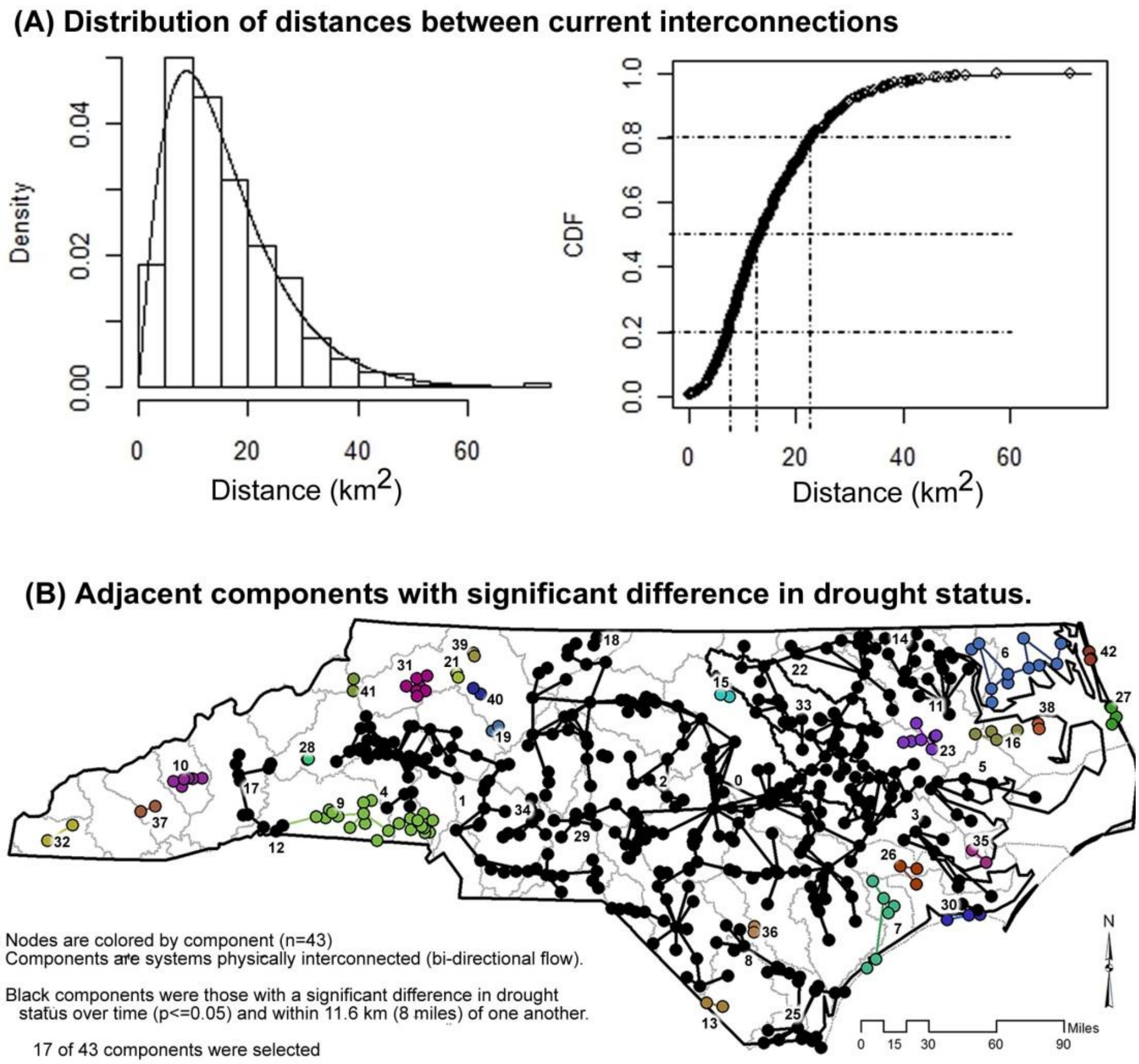


Figure 5.9: (A) Interconnection distances and their distribution (median distance = 11.6 km). (B) Adjacent components within 11.6 km that had significantly different drought status (significant difference in drought probabilities and located within the median distance are highlighted in black).

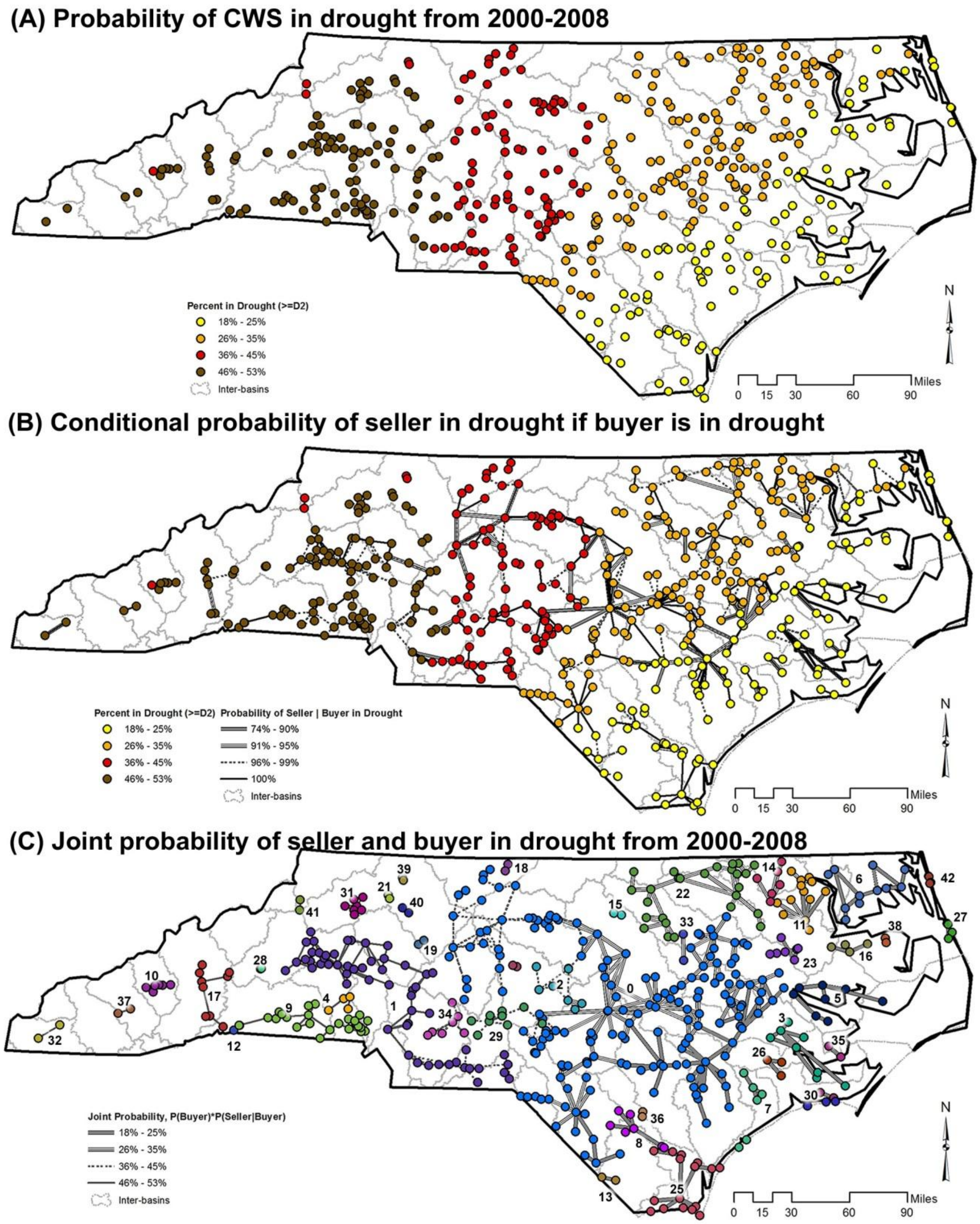


Figure 5.10: Drought probabilities for buyers and sellers. (A) Probabilty of CWS in drought from 2008-2008. (B) Probability of a the seller being in drought conditions when a buyer is in drought conditions. (C) Joint probability of buyers and sellers in drought from 2000-2008.

5.10 Appendix

5.10.1 Future planned interconnections and barriers to interconnections

LWSP's mentioned approximately 20 new interconnections in different phases of completion (Figure 5.11). Many of these interconnections are with nearby adjacent system (e.g. Stoneville is connecting with Deep Water Inc.) to reduce the cost of building an interconnection and pumping water between systems. Central Nash is adding an interconnection to Rocky Mount to meet growing demand from increasing population (LWSP, 2012). Saluda is using grant money to construct an interconnection to Tyron and Columbus (Component 12), which will also connect to Asheville and Hendersonville (Component 17) for emergency purposes. West Carteret Water Corp (currently not connected) has plans to connect to Morehead City and Newport (Component 30) to develop a 3-way emergency interconnection; however, they do not yet have adequate funds to undertake the project.

Distance and finances are two of the largest barriers to establishing interconnections (Figure 5A.1). The following systems listed distance as the sole reason for not having an emergency interconnection: Lansing, Lenoir, Linden, Lowell, Ocracoke (accessible only by ferry), Peachland, Pfeiffer-N Stanly Water Association, Ramseur, Southern Outer Banks, and Stokes County. Several of these systems have regular interconnections, but no opportunity for additional interconnections. Distance is also tied to finances. For example, Sims is located 3 miles from the closest possible connection to Wilson County, but the project remains financially infeasible unless Wilson County extends closer to Sims (LWSP, 2012). Some CWS, such as Pilot Mountain and Yadkinville do not have emergency interconnections because the cost exceeds their financial capacity, and interconnections are more expensive to build and maintain in mountain regions due to topography. For example, Sugar Mountain would have to pump water uphill from Banner Elk, which is too costly to achieve adequate water pressure (LWSP; 2012).

The water capacity of surrounding systems can also be a barrier to the establishment of interconnections. For example, Sanford, Oxford, and Pamlico County do not have interconnections because there are no nearby systems with adequate water supply capacity or ability (service lines are too small) to meet their needs (LWSP; 2012). In addition, some CWS interconnections are looped. Oakboro's primary source of water is through a contract with Albemarle and they have an emergency contract with Stanly County. However, Stanly County also purchases their water supply through Albemarle County. Lastly, contracts between CWS can be problematic for establishing interconnections. For example, the town of Stanley has an exclusive contract with Mount Holly that legally prevents them from interconnecting to another CWS. Another example would be an agreement between Mount Airy and Dobson, where construction was nearly completed when Dobson backed out of the agreement (LWSP; 2012).

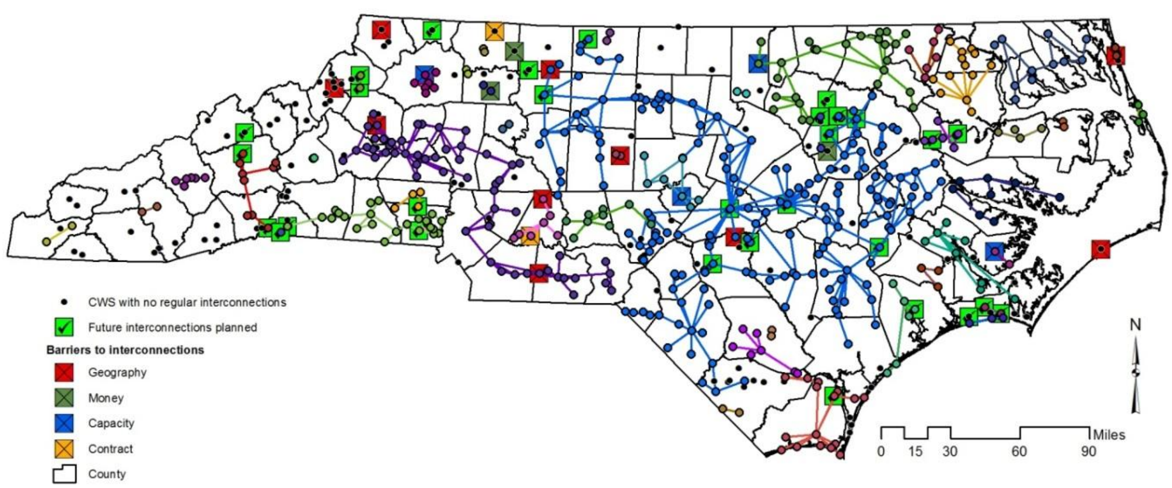


Figure 5.11: Reported future interconnections and barriers to interconnections (LWSP, 2012)

5.11 References

Andreadis, K.M. and D.P. Lettenmaier. 2006. Trends in 20th Century Drought over the continental United States. *Geophysical Research Letters* 33, L10403, doi. 10.1029/2006GL025711.

Andreadis, K.M., E.A. Clark, E.A., A.W. Wood, A.F. Hamlet, and D.P. Lettenmaier. 2005. Twentieth-Century Drought in the Conterminous United States. *Journal of Hydrometeorology* (6): 985-1001.

Carbone, G.J., J. Rhee, H.P. Mizzell, and R. Boyles. 2008. A regional-scale drought monitoring tool for the Carolinas. *Bulletin of the American Meteorological Society* 89: 20-28.

Carbone, G.J. and K. Dow. 2005. Water resource management and drought forecasts in South Carolina. *Journal of the American Water Resources Association* 41 (1): 145-155

Carter, N.T., A. Abel, E.H. Buck, K. Alexander, M.L. Corn, S.M. Kaplan, and C. Brougher. 2008. Apalachicola-Chattahoochee-Flint (ACF) Drought: Federal Water Management Issues. Congressional Research Service Report for Congress. RL34326.

Crase, L. 2007 (ed.) *Water Policy in Australia: The Impact of Change and Uncertainty*. Resources for the Future, Washington D.C..

Dow, K. R.L. Murphy, and G.J. Carbone. 2009. Consideration of User Needs and Spatial Accuracy in Drought Mapping. *Journal of the American Water Resources Association* 45 (1): pp. 187-197. Doi: 10.1111/j.1752-1688.2008.00270.x

Feldman, D.L. 2009. Preventing the repetition: Or, what Los Angeles' experience in water management can teach Atlanta about urban water disputes. *Water Resources Research* 45, W04422, doi: 10.1029/2008WR007605.

Fransen, T. 2012. Status of inter-basin transfers in NC: regulation of surface water transfers. NCDENR Division of Water Resources presentation.

Hill, T. and Polsky, C. 2007. Suburbanization and drought: A mixed methods vulnerability assessment in rainy Massachusetts. *Environmental Hazards* 7 (4), pp. 291-301.

Kirsch, and G. Characklis. 2008. Regional strategies for meeting water demand in the Central Coastal Plain of North Carolina. White Paper: http://sogweb.sog.unc.edu/Water/index.php/File:CCPCUA_summary.pdf. *Last Accessed Jan 2012.*

Lemos, M.C. 2008. What Influences Innovation Adoption by Water Managers? Climate Information Use in Brazil and the United States. *Journal of the American Water Resources Association* 44 (6): pp. 1288-1396. Doi: 10.1111/j.1752-1688.2008.00231.x

LWSP (Local Water Supply Plans). 2012. North Carolina Department of Environment and Natural Resources Division of Water Resources. *Last Accessed February 2012*. http://www.ncwater.org/Water_Supply_Planning/Local_Water_Supply_Plan/search.php

McLaughlin, J.W. 2010. North Carolina Water Resources: the future is being formed now. Annual Conference at North Carolina American Water Works Association and the Water Environment Federation. *Last Accessed Feb 2012.* *http://www.ncsafewater.org/Pics/Training/AnnualConference/AC10Technical Papers/AC10_Water/Water_T.PM_02.15_McLaughlin.pdf*

Mitchell, J.K., 2006. Urban Disasters as Indicators of Global Environmental Change: Assessing Functional Varieties of Vulnerability: In: *Earth System Science in the Anthropocene*, Ehlers, E. and T. Kraft (Editors) Springer Berlin Heidelberg, Germany: pp. 135-152.

Moreau, D.H. and L.U. Hatch. 2008. Statutes governing water allocation and water resource planning in South Atlantic states. Report by the Water Resources Research Institute of the University of North Carolina, Chapel Hill.

NRC (National Research Council). 2011. Global change and extreme hydrology: testing conventional wisdom. Report by the Committee on Hydrologic Science Water Science and Technology Board. *National Academies Press*, Washington, D.C. ISBN 978-0-309-21768-2, pp. 45

Patterson, L. and S. Eskaf. 2011. Assessment of Current and Potential Water System Interconnections in North Carolina. *Report to NCDENR PWSS division.* Environmental Finance Center at the University of North Carolina, Chapel Hill, NC: 46 pp.

Palmer, R.N. & Characklis, G.W. 2009. Reducing the costs of meeting regional water demand through risk-based transfer agreements. *Journal of Environmental Management* 90, pp. 1703-1714.

Pulwarty, R.S., K.L. Jacobs, and R.M. Dole, 2005. The hardest working river: Drought and critical water problems in the Colorado River Basin *In:* D.A. Wilhite (ed.) *Drought and Water Crises: Science, Technology, and Management Issues*. CRC Press. Boca Raton, FL. pp. 3-29.

Sabo, J.L., T. Sinha, L.C. Bowling, G. H.W. Schoups, W.W. Wallender, M.E. Campana, K.A. Cherkauer, P.L. Fuller, W.L. Graf, J.W. Hopmans, J.S. Kominoski, C. Taylor, S.W. Trimble, R.H. Webb, and E.E. Wohl. 2010. Reclaiming freshwater sustainability in the Cadillac Desert. *PNAS* 107 (50): 21263-21270, doi: 10.1073/pnas.1009734108

Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change. *Journal of Climate* 22: 5021-5045, doi: 10.1175/2009JCLI2683.1.

Sun, G., S.G. McNulty, J.A.M. Myers, and E.C. Cohen. 2008. Impacts of multiple stresses on water demand and supply across the Southeastern United States. *Journal of American Water Resources Association* 44 (6): 1441-1457, doi: 10.1111/j.1752-1688.2008.00250.x

Trenberth, K.E. 2011. Changes in precipitation with climate change. *Climate Research* 47: 123-138, doi: 10.3354/cr00953.

van der Zaag, P., and J. Gupta. 2008. Scale issues in the governance of water storage projects, Water Resources Research 44, W10417, doi:10.1029/2007WR006364.

Water Wiki. 2012. Interbasin transfer. http://sogweb.sog.unc.edu/Water/index.php/Interbasin_transfer. *Last Accessed Dec 2012.*

Water Wiki. 2010. Drought Response. http://sogweb.sog.unc.edu/Water/index.php/Drought_Response. *Last Accessed Dec 2010.*

Weaver, J.C. 2005. The Drought of 1998-2002 in North Carolina – Precipitation and Hydrologic Conditions. USGS Scientific Investigations Report 2005-5053: pp. 98.

Whisnant, R. and B. Holman. 2010. Report of the Water Allocation Study of the Environmental Review Commission of the North Carolina General Assembly: 30 pp.

Zhang, Q. 2009. The South-to-North Water Transfer Project of China: Environmental Implications and Monitoring Strategy. *Journal of American Water Resources Association* 45 (5): 1238-1247, doi: 10.1111/j.1752-1688.2009.00357.x

CHAPTER 6

SUMMARY OF DISSERTATION FINDINGS

The goal of this dissertation was to quantitatively understand how streamflow conditions have changed in the South Atlantic in order to inform ongoing policy discussions regarding water allocation. Ideally, the South Atlantic is striving to proactively set in place legislation and infrastructure to address water scarcity before the problem becomes chronic. Drought, particularly hydrological drought, has been the catalyst to much of the current water policy reform in the South Atlantic and provides a glimpse of the potential stress water systems will experience in the long-term as population continues to grow. It is necessary to make the tough, and often unpopular, decisions now to change the way water resources are managed in order to avoid more suffering and difficulty in the future (Thebault, Forthcoming).

Water management is designed to ensure adequate water supply and protect water quality both now and for future populations. In addition, water management is bounded by how hydrologic extremes are defined and characterized (from flood control to drought; Stakhiv, 2011). Thus, water management decisions are based on a complex set of cost-benefit analyses that ultimately rests upon hydrologic frequency analysis (Stakhiv, 2011). This dissertation took a slightly different approach from typical hydrologic frequency analysis by exploring trends in streamflow for watersheds that are subject to a broad range of human influences, rather than looking only at unmodified basins. It is the human influenced basins that contribute to water supply and have the greatest potential to be directly impacted via management strategies.

Chapter 2 focused on exploring changes in the average monthly conditions of climate (precipitation and temperature) and streamflow from 1934-2005, 1934-1969, and 1970-2005. The detectability of trends is a function of natural variability, the magnitude of the change we are interested in, and the level of risk we are prepared to accept in statistical testing (Sheffield and Wood, 2008). Precipitation and streamflow had a high level of variability, which is one reason we looked at regional results over multiple time scales to tease out signal verses noise (NRC, 2011). We found that streamflow had significant, decreasing trends during the Mid-20th Century (1934-1969) and Late-20th Century (1970-2005), but few significant trends during the entire period. The lack of trend during the entire period is due to an abrupt increase in precipitation around 1970 that placed the entire region into a wetter hydrologic regime (Figure 6.1). During the Late-20th Century, precipitation showed little change while streamflow decreased. The decrease in streamflow could be a result of the significant increase in temperature that occurred during the Late-20th Century (temperatures had significantly cooled during the Mid-20th Century and are now approaching temperatures similar to the 1930's). Decreasing streamflow during a wetter hydrologic regime could also be the product of human influences, particularly increasing water demand following rapid population grown since the 1970's.

Chapter 3 used the Budyko decomposition method (Wang and Hejazi, 2011) to answer the question of how much climate and humans contributed to changes in mean annual streamflow between the Mid-20th and Late-20th Century. We found that climate contributed to a wetter hydrologic regime throughout the region (0% to 24% increase). Human changes to streamflow varied by basin and served to either amplify (increase by 12%) or minimize (decrease by 18%) the climate effect on streamflow (Figure 6.1). Reservoir storage and population were linked to a decreased streamflow; whereas, agricultural land cover was associated with increased streamflow. Not only can human's impact mean annual streamflow, but hydrologic extremes such as drought are also impacted by land cover change, urbanization, and the operation of water management facilities such as dams, irrigation and water transfers (NRC, 2011).

While the change in average streamflow conditions is important for long-term water supply planning, what often receives priority in management plans are the behavior of extremes, which are the least certain aspects of hydrology (Hirsch, 2011). In Chapter 4, we characterized drought in the South Atlantic and explored changes in drought characteristics of duration, frequency, streamflow deficit, and severity from 1930-2010, 1930-1969, and 1970-2010. We found that 71% of drought events were shorter than 6 months and occurred every 5 to 6 years. However, the South Atlantic also experienced a few drought events that extended between 1 to 3 years (7% of events). There were not many significant changes in drought characteristics during any of the time periods examined, with the exception of a significant increase in the spatial extent of drought from 1970-2010. We also found a significant shift in the probability of adjacent basins being in drought at the same time from the Mid-20th to the Late-20th Century. This shift mirrored the spatial pattern of significant changes in average streamflow found in Chapter 2 with a significant increase (decreasing mean streamflow) in the probability of adjacent basins simultaneously being in drought in the southern portion of the study area (Figure 6.1). The increased likelihood of adjacent basins being in drought conditions have implications for water management plans to augment supply via water transfers from nearby basins during emergency drought conditions.

It is important to translate science regarding hydrologic extremes into agency-relevant policy-actionable knowledge (NRC, 2011). Chapter 5 used the interconnections database of water transfers between water systems in North Carolina as a case study for the ability of interconnections to expand beyond the spatial extent of drought conditions during rare, multi-year drought events. North Carolina had 671 reported interconnections between 581 community water systems (CWS; 66% of CWS had an interconnection). Thirty eight of these CWS were connected to only one other system. The largest group of physically connected systems contained 174 CWS and was located throughout the majority of the Piedmont and the Inner Coastal Plain. We found interconnections were most useful for mitigating drought conditions near the start and end of a drought event and when greater numbers of CWS were connected. We found that once a buying system was in-drought there was an average of 98±3% (range 74 to 100%) probability of the selling system also being in-drought. The high conditional probability of both systems being in-drought conditions simultaneously is not surprising given the relatively short distance between water systems in North Carolina (median=11.6 km). These short interconnections do not seem to be an optimal solution for drought mitigation purposes. However, from a long-term planning perspective, interconnections provide a viable option to redistribute water between water-rich and water-poor systems, as well as by building a safety of margin through redundancy in water supply options.

6.1 Policy Implications

In Chapter 2 we found that streamflow exhibited gradual trends over long periods of time that were punctuated by abrupt and large shifts associated with changes in climate. The presence of both persistent wetter and drier periods that can change abruptly has important implications for water resource management regarding the need to develop the flexibility to change priority management focuses. Water managers in the South Atlantic are efficient in managing the immediate juxtaposition of wet months (e.g., recharging reservoirs in the winter) to dry months (e.g. mandatory water restrictions in the summer) within a year. However, the institutional capacity to manage persistent conditions of wet and dry years of streamflow has not been widely developed.

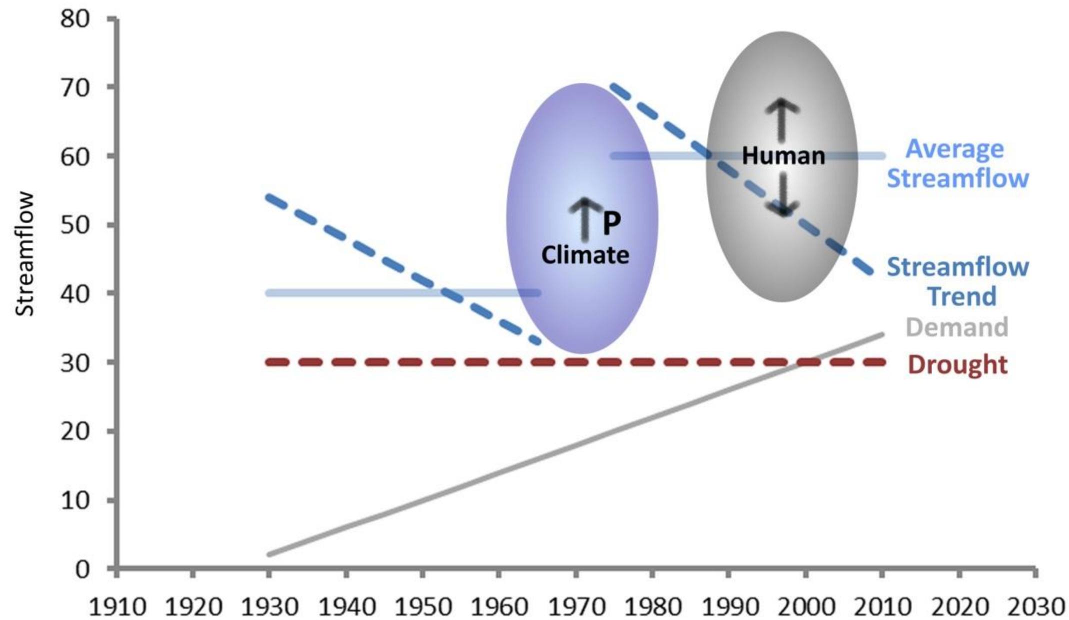
At the watershed scale, water resource managers are also responsible for managing human impacts on water supply (both quality and quantity). Understanding the relative contribution of humans to changes in streamflow is an important first step to being able to efficiently address those impacts. In addition, human impacts on streamflow are potentially easier to address than climate impacts because they are constrained to the basin scale and can be directly influenced through management practices. The direction of some human factors can be predicted with greater confidence, such as the increase in population over the next 20 years and the strain that will be placed on current water supply systems as water demand increases (Figure 4.8).

Highly developed watersheds that have large reservoirs but are characterized by high annual demands relative to annual inflows are at greater risk for being negatively impacted by climate change (VanRheenen et al., 2011). This is particularly true of large cities located in the upper portion of river basins in the Piedmont region of the South Atlantic where the water supply drainage area is relatively small and water demand continues to grow. While the storage capacities of reservoirs can be used to moderate flow variability for a short time period and provide water during drought conditions, a multi-year drought can have significant consequences due to increased water demand and longer periods during which demand exceeds inflows (VanRheenen et al., 2011). The two multi-year droughts in this region resulted in record low streamflow for many basins and emergency conditions for water systems. These two events highlight the increased sensitivity of this area to drought as water demand has grown to approach water supply.

Water resources management has developed a variety of strategies to deal with periods of high demand and low water availability, consisting of long-term infrastructure adaptation to stationary climate signals and shorter term adaptive management measures that center mostly on flexible operations and demand-side management (Stakhiv, 2011). This current system is becoming less effective as the ratio of demand and supply becomes smaller. For example, in North Carolina most water professionals acknowledged that the past, decentralized water resource regulations will soon not be adequate to assure water supply is reliable across the state (Whisnant and Holman, 2010). This is particularly true in the high growth areas of the state, where "much more active and robust state and regional means of managing water demand, sharing water resources, and increasing water storage" are needed (Whisnant and Holman, 2010). Interconnections are an important infrastructure tool to increase regional connectivity and sharing of water resources. Interconnections are costly and do impact the environment so it is important to assess the current network and determine the optimal locations for new interconnections to minimize negative impacts. This may require changing current state policies (e.g. Inter-basin transfer laws) in order to promote the flexibility and confidence needed for CWS to share resources and plan for the future. At the state level, policies must break away from what is comfortable and take risks now to ensure that water will be available where it is needed in the future. Since the drought of 1998-2002 we have seen steps taken away from Riparianism and toward regulating water allocation. This an important first step that must continually be informed by monitoring changes in climate, human activities, and streamflow, as well as continually assessing the ability of current water infrastructure to perform under normal and adverse conditions.

6.2 Figures

(A) Time series of short and long-term water supply trends



(B) Spatial patterns of water supply from 1970-2005

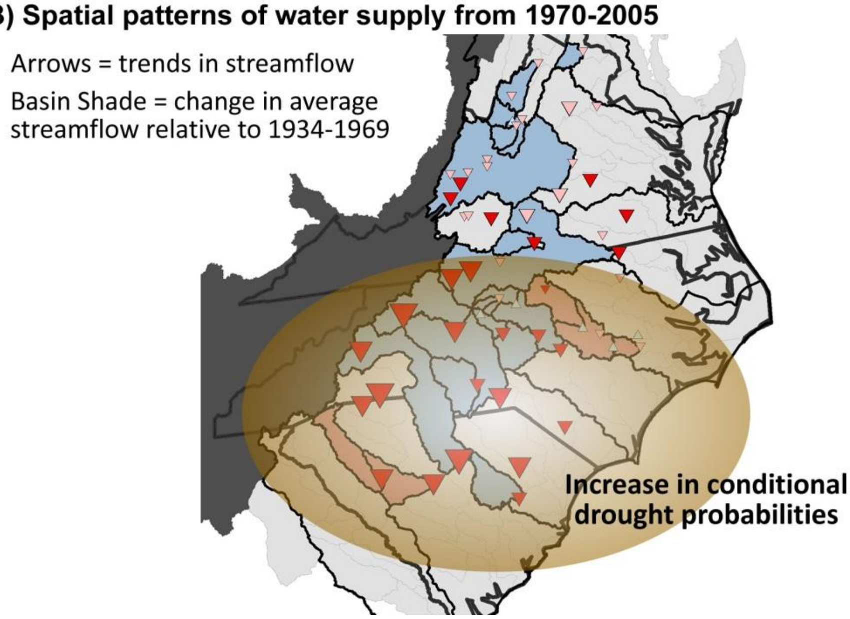


Figure 6.1: Illustration of temporal and spatial changes in water supply for the South Atlantic. (A) Time series of average water supply, trends in water supply, and direction of influence by climate and human factors on streamflow. No significant trend in drought. Demand has increased throughout the region. (B) Arrows show trends in streamflow from 1970-2005 and the blue (red) shade indicates increasing (decreasing) streamflow relative to 1934-1969. The highlighted region had higher conditional drought probabilities in the Late-20th Century relative to the Mid-20th Century.

6.3 References

Hirsch, R.M. 2011. A perspective of Nonstationarity and Water Management. *JAWRA* 47 (3): 436-446. DOI: 10.1111/j.1752-1688.2011.00539.x

NRC (National Research Council). 2011. Global change and extreme hydrology: testing conventional wisdom. Report by the Committee on Hydrologic Science Water Science and Technology Board. National Academies Press, Washington, D.C. ISBN 978-0-309-21768-2, pp. 45

Stakhiv, E.Z. 2011. Pragmatic approaches for water management under climate change uncertainty. Journal of American Water Resources Association 47 (6): 1183-1196, doi: 10.1111/j.1752-1688.2011.00589.x

Sheffield, J. and E.F. Wood. 2008. Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. Journal of Climate 21: 432-458, doi: 10.1175/2007JCLI1822.1

Thebaut, J. Forthcoming. Running Dry: Beyond the Brink. Last accessed February, 2012. http://awramedia.org/mainblog/2011/12/07/preview-jim-thebauts-running-dry-beyond-the-brink/

VanRheenen, N.T., R.N. Palmer, and R.N. Hahn. 2003. Evaluating potential climate change impacts on water resource systems operations: Case studies of Portland, Oregon and the Central Valley, California. Water Resources Update 124, 35-50.

Wang, D. and M. Hejazi. 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resources Research 47 (W00J12), doi: 10.1029/2010WR010283.

Whisnant, R. and B. Holman. 2010. Report of the Water Allocation Study of the Environmental Review Commission of the North Carolina General Assembly: 30 pp.