ABSTRACT

Assessing Future Water Resources: The Influence of Climate Change, Population Growth and Land Use Change in the Lower Cape Fear Basin, North Carolina

By

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With the possibility of future fresh water shortages increasing, a methodology for predicting future water availability conditions is needed. This research outlines a methodology to estimate these conditions based on the influence of climate change, land use change, and population growth. The method is based on the USGS Thornthwaite monthly water balance model and can incorporate estimates of climate change and land use change parameters to assess future water resources based on predicted monthly fluxes of the water balance. The methodology is demonstrated by analyzing watersheds in the lower Cape Fear River basin located in southeast North Carolina.

The southern United States is a rapidly growing region. Trends present in the population data are used to produce future estimates of population for the basin. Precipitation and temperature estimates based on Intergovernmental Panel on Climate Change (IPCC) predictions and current climatology are inputs to the model. Projected increases in impervious surface cover due to population growth and urbanization are incorporated through the model runoff factor.

Water stress indicators are used to categorize the region as water rich, water stressed, or water scarce. Scenarios incorporating regional predictions of climate change indicate a decrease in summer soil moisture minima and increases in summer water deficits. The impact of impervious surface cover enhances these deficits. Ensemble runs indicate a shift toward water stress in the lower Cape Fear River basin in the future, due to a warming climate as well as increased demand. While climate change has a significant impact on water resources in the region, population growth has the most substantial impact as it not only impacts demand, but climate and land use as well.

Assessing Future Water Resources: The Influence of Climate Change, Population Growth and Land Use Change in the Lower Cape Fear Basin, North Carolina

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CHAPTER ONE: INTRODUCTION

Demand for fresh water in the United States has been a concern for many years, although this concern has been primarily limited to western states such as California. However, in recent years,severe drought has struck the southeastern United States, exposing potential water shortages. Acknowledging the risk of water scarcity in the Southeast, a region which has historically been thought of as water rich, is imperative to sustain water under future conditions. Primary reasons for concern are population growth and climatic/environmental change. According to the US Census, North Carolina was the 6th fastest growing state from 2000 to 2008. The increasing population of the state increases demand which, coupled with climatic/environmental change, could increase the risk of water scarcity.

Anthropogenic influences on the hydrologic cycle are numerous. As a result of climate change, precipitation and evapotranspiration rates around the globe ebb and flow. These changes can alter the seasonal frequency, intensity, and location of precipitation. While some regions experience increases in precipitation, others experience decreases, and the frequency and intensity of the precipitation can have a substantial impact on the water supply. For instance, less frequent precipitation events with more intense precipitation could increase the yearly precipitation values, but it could be as runoff rather than infiltrating the hydrologic network. Variations in precipitation frequency and intensity can create seasonal water shortages within a basin relating to the soil moisture capacity of the watersheds and the influence of evapotranspiration on the water balance. If summer precipitation decreases, the water deficits in that basin could increase due to the fact that evapotranspiration will be highest in the summer months.In addition to water shortages, alterations in frequency and intensity can also present water quality issues, therefore decreasing available fresh water. According to the Intergovernmental Panel on Climate Change(IPCC) fourth assessment (2007), all region'swater resources could potentially be negatively impacted by climate change. Some regions will experience a decrease in runoff, while others will experience an increase, but the increase also comes with a shift in seasonality. Therefore, even an increase in precipitation has negative impacts, given shifts in seasonality, which can increase yearly water deficits (IPCC 2007). For instance, a five percent increase in winter precipitation will not offset a five percent decrease in summer precipitation due to enhanced evapotranspiration in summer months from warmer temperatures.

While climate change is important, it is not the only anthropogenic influence on water resources. Land use is also an important variable to consider. There are two potential avenues land use is altered. The land can be directly altered by humans and land can be indirectly altered by humans through anthropogenic climate change.Impervious surfaces are a major concern when it comes to land use change. Additional impervious surface due to urbanization modifies many aspects of the water balance, including infiltration rates, which in turn affects the soil moisture and runoff production of a region. Impervious surfaces can also alter regional evapotranspiration rates, which have the potential to influence precipitation globally and locally. Climate change can alter the type and amount of vegetation in a region, therefore changing land cover of a region. One effect of this is desertification, where vegetated land becomes incapable of supporting that vegetation. This is an important impact of climate change, but it is not included in this research.

In addition to anthropogenic influences on the hydrologic cycle and water supply, anthropogenic changes to a region or watershed also influence the demand for water, and thus change not just physical hydrology, but more broadly water resources. Population growth, land use change, and climate change can all influence water resources and therefore need to be addressed. Population growth increases demand which can place stress on water supplies. With population growth also comes land use change and pollution, which degrade the available water supply. Therefore population growth affects water resources in a variety of ways. While the impact of climate change on water resources seems apparent since it alters precipitation and temperature, factors such as population growth and land use change often have a more substantial impact.

The Lower Cape Fear River basin, located in southeastern North Carolina is an intriguing study area. It is a rapidly growing coastal region where land use is constantly evolving. An understanding of how fluctuations in population, land use, and climate will influence the Cape Fear River basin is crucial, primarily due to the population growth rate. Understanding the impact of these variables will aid in determining how much growth the region can sustain. Knowledge of how population growth and land use affect the hydrologic cycle, as well as how climate change could impact future precipitation, evapotranspiration, and water consumption, will shed light on the potential for water scarcity.

The objective of this research is to analyze the potential impact of climate change, population growth, and land use on water resources at the local level, by modeling monthly water fluxes and uncertainties under various scenarios, and to explore possible metrics for assessing these impacts. To explore the influence of climate change, population growth, and land use, water stress indicators are utilized to compare availability to demand. This approach allows an analysis of whether the region is in danger of becoming water stressed or even water scarce in the future. Local trends of land use and population growth along with large scale predictions of climate change allude to the possibility of fluctuations in water resources. The objective is met by performing a case study and using that to provide a framework that can be applied to other environments.

This case study focuses on the lower Cape Fear River basin, a region which includes New Hanover and Brunswick counties, two rapidly growing areas. A water balance modelis established for the region, which allows water resources to be assessed under various future climatic, population, and land use scenarios. One result of this research is a better understanding of the potential issues that could arise in this region, along with a framework for examining potential water scarcity.

This study addresses questions relating to quantifying and estimating the influence of climatic and environmental change factors on water resources. First,**how would a changing climate influence the physical/environmental availability of water in the lower Cape Fear River basin of North Carolina?**In order to address this question, large scale predictions of precipitation are analyzed to assess what the predictions are for the region. Analysis of the predictions focuses on the climate features that most directly affect water balance and water resources: overall yearly precipitation rates, yearly distribution of precipitation,andchanges in temperature. The analysis attempts to illustrate the estimated impact of temperature changes based on its appearance in evapotranspiration values.Second,**what role does environmental change play in the water availability of the lower Cape Fear River basin?**Based on current rates and GIS analyses of impervious surfaces,this project assesses the impact of land use change on the water balance. Finally, to provide an overall assessment of these factors on water resources, this work explores, **what methods or metrics can we use to express the effect of the combined influences of population growth, environmental and climate change?**

CHAPTER TWO: UNDERSTANDING CLIMATE AND WATER DYNAMICS

Previous research addressing water resources hasvaried by location and methodology. In the United States, the majority of the research focuses on western states. Numerous case studies examine the impact of either climate change or urbanization on water resources. More extensive case studies attempt to incorporate both variables, which can provide a clearer picture for future conditions. The following is a review of the research examining climate change, population, land use, or a combination of the three. In addition to the research depicting previous case studies, a review of research illustrating the implementation of a water balance is included.

Influences of Climate Change on the Hydrologic Cycle

Understanding how climate affects hydrologic factors such as evapotranspiration and runoff isessential to evaluating water resources.Various regions in the United States are alreadyexperiencing water resources deficits. The Western United States has faced this problem for many years.A warming climate can affect multiple aspects of the hydrologic cycle. Factors to consider when assessing water resources include precipitation, evapotranspiration, runoff, and soil moisture, all of which can be altered by climate change. Climate change could transition a water stressed region to a water scarce region or vice-versa. According to water stress indicators such as the Falkenmark indicator, water stress is defined as water resource availability below 1700 m^3 per person per year. A region is considered water scarce when water availability falls below 1000 m^3 (Rijsberman 2006).

A warming climate can increase precipitation and evapotranspiration rates while also altering the frequency, intensity, and location of the precipitation (Arnell 1999). Temperature is a determining factor when examining the hydrologic cycle. Therefore, fluctuations in climate should be expected to alter the cycle, due in large part to the sensitivity of saturation vapor pressure with fluctuations in temperature (Milly et al. 2005). The intensity of precipitation events is likely to increase as a result of global warming, as the saturation vapor pressure increases with an increase in temperature. Therefore, the moisture content in the atmosphere increases. At the same time, increaseddownwelling infrared radiation due to rising greenhouse gas concentrations affects not only temperature, but evaporation as well. This increase in evaporation increases the moisture content of the atmosphere, which in turn enhances precipitation events (Trenberth 1999). The impact of this will vary across the globe such that some regions will experience more precipitation while others will see declines. This could transition some regions from one climate type to another.Huntington (2005) analyzed historical data to see if trends exist supporting the hypothesis of intensification of the water cycle with warming. While results showed intensification, there is some spatial and temporal uncertainty that relate to incomplete data and some contradictory analyses (Huntington 2005). Thus, the influence that climate change has on the hydrologic cycle needs to be addressed further. In order to account for the effect of climate change on the hydrologic cycle, climate predictions must be utilized. Predictions based on global climate models, such as those produced by the IPCC, can be incorporated to examine future hydrologic conditions(IPCC2007).

Influence of Climate Change in the Southeastern United States

Warming in the Southeastern United States, as projections from the IPCC indicate, could present problems for water resources in the region due to the effect it has on precipitation recycling and runoff. Precipitation recycling is the redistribution of water locally that was evaporated from the surface (Brubaker et al. 1993). Warming trends in the climate will increase evapotranspiration in the region which will decrease runoff (Mulholland et al. 1997), therefore altering the amount of available surface water. Alterations in precipitation recycling will increase the frequency of localized precipitation (Mulholland et al. 1997). According to Hurd et al. (1999), the southern United States may see an increase in precipitation, but the yearly distribution will likely come more in the form of intense precipitation events, causing water quality and flooding issues. A study conducted by Robinson (2006), which focused on North Carolina with some analysis of the Cape Fear River, found little deviation from the average yearly precipitation in the 20th century. However, the yearly distribution was altered, with autumn precipitation increasing and summer precipitation decreasing at least ten percent (Robinson 2006). A modeling approach utilizing Hadley Centre (HadCM2 and HadCM3) climate projections incorporated by Arnell (1999) indicates that North Carolina would see increased precipitation due to a warming climate, but it will come in the form of more intense precipitation events. If that is what the future holds, measures, by way of infrastructure, must be taken in order to harness the water.

While most agree that climate change can influence water resources, it is difficult to assess the impact. The IPCC (2007) predictions project a warming trend over all of North America with variations in severity depending on the region. As a result of the warming trend, the IPCC predicts an intensification of the hydrologic cycle due to the relationship between temperature and saturation vapor pressure. While some regions that are already dry will most likely experience further dryness, the IPCC predicts an increase in precipitation year round in the Southeast United States. In addition, the temperature is expected to increase in the region, causing an increase in evaporation. The distribution of precipitation is also expected to change. If summer precipitation in the Southeast decreases as some research indicates (IPCC 2007 and

Robinson 2006), the yearly deficits could increase as a result of less precipitation and more evaporation.

Incorporating Climate Change Scenarios in Water Resource Planning

In order to quantify the risk of water stress in a region due to climate change, certain techniques for predicting future conditions, such as precipitation and evapotranspiration, must be incorporated. Techniques, as utilized in the past, consist of either statistical analysis of past data or modeling approaches. Much of the previous research has incorporated climate models in order to estimate future conditions. While both methods have been utilized, the modeling approach is most often incorporated. California, where water availability has long been a concern, is the focus of many case studies in the UnitedStates regarding water resources. Even though the methodological approaches taken in these studies varied, results were similar (Vicuna and Dracup 2007). Runoff, from snowmelt, has been declining and initiating earlier in the year due to warming (Vicuna and Dracup 2007). While the hydrology of this region is different than that of the Southeast, the methods of assessing water resources are pertinent. The difference in hydrology is primarily due to the role that seasonal snowmelt plays in the California study area. California along with much of the Western United States, relies on water from snowmelt yearly. An important thing to note from the review by Vicuna and Dracup (2007) is that the various methodologies that were utilized produced similar results. According to the ensemble of studies reviewed, California’s water resource infrastructure could be compromised by a warming climate (Vicuna and Dracup 2007).

Studies attempting to determine the impact of climate change on water resources produce varying results depending on location, as some regions will experience increased precipitation and others will decrease, but they consistently show fluctuations in yearly averages of water availability (Hurd et al.1999, Robinson 2006, Vicuna and Dracup 2007). The methodological approaches used incorporate predicted precipitation and estimated evapotranspiration rates rooted in global climate models. In addition to global climate models, predicted values are incorporated,derived fromhistorical trends. Both methods could be beneficial in examining future water resource conditions in the lower Cape Fear River basin. While regional climate models would seem to make more sense when looking at a localized area, the reliability of downscaled global climate models is questionable, especially in regards to North Carolina (State Climate Office of North Carolina 2011). However, predicted rates utilizing observed local trends can constitute a more reliable regional approach. Analysis of the climate prediction approaches can provide insight into what the future climate in the Cape Fear region will be. These approaches can provide both rates and values of precipitation and temperature, while also addressing seasonality.

Anthropogenic Influences on Hydrology

Land use can have multiple effects on water resources. A major issue associated with land useis a decrease in fresh water due to contamination from runoff, caused by additional impervious surfaces. The addition of buildings and impervious surfaces that come with population growth increase the flashiness/magnitude of runoff following precipitation events (Praskievicz and Chang 2009). This increase in amount and speed of runoff can increase the contaminants in the water supply and also make it more difficult to control the water from extreme events to prevent flood damage. In addition to presenting water quality issues, impervious surfaces also decrease evapotranspiration as a result of decreased vegetation and infiltration capacity (Praskievicz and Chang 2009).Local hydrologic cycles depend on precipitation and evapotranspiration.   Alterations in evapotranspiration rates influence the local precipitation cycle.The addition of impervious surfaces can have a substantial impact on the water balance of a region or watershed.Other anthropogenic induced land use change such as deforestation can also influence the water balance. However, in the Lower Cape Fear basin there is very little deforestation and a great deal of population growth, which leads to urbanization and additional impervious surface cover.

Population growth can have a substantial impact on local watersheds. Demand for fresh water is the obvious problem associated with population growth, since it places further stress on the water supply. Population stresses on water resources are substantial and rapidly growing. Over half of the available runoff is already being utilized by humans either by consumption and agriculture or contamination (Postel 2000). The stress on water supply is expected to grow to 70% by 2025, with the urban population expected to reach 61% of the total global population, an increase of 15% since 1996 (Postel 2000). The fact that large urban areas in the lower Cape Fear River basin, such as Wilmington, NC relyheavily on surface water(North Carolina Department of the Environment and Natural Resources 2011) does not bode well for future water resource availability. If the available surface water becomes too stressed in the region, the lower Cape Fear aquifer will have to be tapped in order to compensate for the excess stress, which could also present problems. Excessive withdrawals from the aquifer could lead to salt water intrusion in the aquifer, decreasing available fresh water. However, even though human consumption of water increases with population growth, according to Roy et al. (2005), the majority of the anthropogenic fresh water withdrawals are used for agriculture and energy production. Therefore, technological advances in these areas could decrease demand. However, with population growth, land use change arises, which can also be a hindrance, due to the addition of impervious surfaces to accommodate the growth.Thus, population growth has the potential to impact local water balances and availability in a variety of ways.

Assessing Water Resources

Water balance modeling is a common and proven method for assessing future conditions. Sun et al. (2008) created a watershed budget for the southeast United States,whichincorporates historical data and future predictions of water use, climate conditions, population, and land use. In addition to creating a watershed budget, Sun et al. (2008) implemented a water supply stress index to determine how stressed the region would be in the future due to further land use change, population growth, and climate change.

In order to predict the future of water resources,it is necessary to understand current and historical conditions. Once variables such as precipitation, evapotranspiration, and land use patterns are understood, a model (water balance) can be utilized to evaluate the state of future water resources, under varying climatic and land use conditions. One of the primary goals of a water balance is to predict future water resources under various climate change scenarios (Xu and Singh 1998). Kutzbach et al. (2005) used multiple climate predictions from the IPCC to appraise changes in regional water balances due to fluctuations in temperature, precipitation, and evaporation rates. Water balance models have proven to be effective in assessing hydrologic issues that arise due to climate change (Xu and Singh 1998). Impacts due to land use change can also be estimated with a water balance model, as D’Almeida et al. (2006) demonstrated by looking at the influence of deforestation on surface hydrology.

The implementation of such a model, which takes into account climate and land use,provides valuable insight into future conditions in the study area. While in the past this method may not have been credible due to the uncertainty surrounding climate models, global climate models are proving to be effective in predicting climatic conditions. Hypothetical precipitation and evapotranspiration rates, based on statistical analysis at the local level, can provide a more regional approach to the models.

Water balance models are essentially a "monthly accounting procedure" (United States Geological Survey 2010), as suggested in the following example of a simple water balance equation (Equation 1) (Dingman 2008).

Equation 1

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S$$

P = Precipitation
G_{in} = Ground water in
Q = Stream outflow
ET = Evapotranspiration
G_{out} = Ground water out
ΔS = Change in storage

As can be seen, a water balance model documents water availability, but does not determine if the output will meet the needs of the population. For this, water stress indicators are beneficial to evaluating the extent to which consumption rates exceed or approachavailable fresh water. "When an individual does not have access to safe and affordable water to satisfy her or his needs for drinking, washing or their livelihoods we call that person water insecure. When a large number of people in an area are water insecure for a significant period of time, then we call that area water scarce" (Rijsberman 2006, p.6).Falkenmark et al (1989) illustrate four categories of water scarcity,two of which are related to climate, while the other two have human influences. Climate related categories include: "type a, aridity, which is reflected in a short length of growing season; and type b, intermittent droughts, which is reflected in recurrent drought years in which there is risk of crop failure" (Falkenmark et al. 1989, p.259). The anthropogenic categories are "type c, landscape desiccation, which is due to soil degradation and reduces local accessibility of water and sometimes referred to as man-made drought; and type d, water stress, which is due to too large a population per unit of water available from the water cycle"(Falkenmark et al. 1989, p.260). Using a water stress index such as that produced by Falkenmark et al. (1989) can help determine whether the future renewable water resource levels in a region will be sufficient. The use of water stress indicators allows the results to be tied together in order to make predictions about the sufficiency of future water resources.

CHAPTER THREE: RESEARCH OBJECTIVES AND STUDY AREA

Much of the previous research assessing the vulnerability of water resources is broad, which can provide useful insight into how global water resources respond to global warming. However, while it is useful to examine the big picture, larger study areas increase the potential for error when applying the results on a local scale. Examples of studies which assess broad regions include Sun et al (2008), which concentrates on the Southeastern United States, and Roy et al. (2005) who study the whole United States. Results from the Roy et al. (2005) study indicate that population growth does not have a substantial impact on the demand for water due to technological advancements in agriculture and energy production. However, these results were based on a broad region. If the study had beenundertaken using a finer scale, such as the rapidly growing lower Cape Fear basin, their results may have shown a substantial impact. Focusing on a smaller size region allows for a more detailed study, while some sacrifices must be made in the reliability of the climate predictions, including the fact that large scale climate predictions are applied to a much smaller study area. Conducting research on finer scales could improve upon our knowledge of what the future holds under different climate scenarios. Therefore, assessing future water resources in the lower Cape Fear River basin is the focus of this study.

Probability based assessments of climate impacts and growth changes are applied to provide envelope scenarios. How to present scarcity and scenario information is also explored, incorporating previous methods of evaluating the influence of climate and land use. Thus, the research brings broad scale metrics and an easily applicable methodology to a local region with the goal of producing understandable, useful indices of scarcity and uncertainty, as well as information on the importance of various factors, which could guide policy development or resource allocation. This research provides insight into the region and provides a framework for future studies.

Water balance modeling suppliespertinent informationto aid in answering the research questions presented earlier. The use of a water balance addresses the primary research questions. Future temperature and precipitation rates according to large scale regional climate predictions from the IPCC along with future impervious surface cover extrapolated from current rates are inputs for the water balance. While downscaling regional climate predictions can introduce uncertainty into the analysis, one has to start somewhere in modeling water availability.Given that caveat, the availability of water in the future can be estimated through this modeling approach. Once the availability of water is estimated, water stress indicators are established in order to tie the availability to anticipated demands of future populations. This analysis allows for a classification of future conditions, whether it is water rich, water stressed, or water scarce.

Study Area

Much of the United States could be at risk to water scarcity in the future; however the purpose of this research is to assess a rapidly growing region in the Southeastern United States. Therefore, the region of emphasis is that of the Lower Cape Fear River basin (Figure 1). This basin is located in eastern North Carolina and provides various landscapes, from densely populated urban land to rural farm land and forest cover. Table 1 presentsthe average climatic conditions for the southern coastal plains in which most of the Lower Cape Fear River basin is contained. Average precipitation for the region is 50.92 inches per year (1293.37 mm), and mean annual temperature is 61.77^{o} F (16.5^{o} C). These data are based on climate observations from 1950-2009, (State Climate Office of North Carolina 2010). Seasonal averages, which are important when examining yearly deficits within the regionare also depicted in Table 1.

The Cape Fear River basin is the largest in North Carolina.Contained within the Lower Cape Fear River basin is Wilmington, NC, which is the largest metropolitan area in the basin. The city has over 100,000 people with almost 200,000 people residing within the metropolitan area (City of Wilmington 2009). Unlike many coastal Carolina areas, much of the water utilized in this region is surface water, and therefore surface water is the focus of this study. The stream network of the Lower Cape Fear is extensive (Figure 1). The distribution of population in the basin is depicted in Figure 2. The most densely populated watersheds are centered around New Hanover County in the southern basin, however watersheds in the northern basin, in and around Harnett County, also have high values, as this area is in close proximity to Fayetteville and Raleigh, NC.

Table 1

Average Precipitation and Temperature for the Southern Coastal Plain Of NC (1950-2009)

Monthly Precipitation and Temperature

Month	Precip(in)	Temp(F)
Jan	3.82	43.78
Feb	3.53	46.21
Mar	4.17	52.85
Apr	3.08	61.35
May	3.94	68.94
June	5.04	75.87
July	6.38	79.34
Aug	5.96	78.28
Sep	5.33	72.77
Oct	3.27	62.43
Nov	3.10	53.70
Dec	3.30	45.79
Total/Average	**50.92**	**61.77**

Seasonal Precipitation and Temperature

Season	Precip (in)	Temp (f)
Spring	11.19	61.05
Summer	17.37	77.83
Autumn	11.71	62.96
Winter	10.65	45.26

Source: State Climate Office of North Carolina (2010)

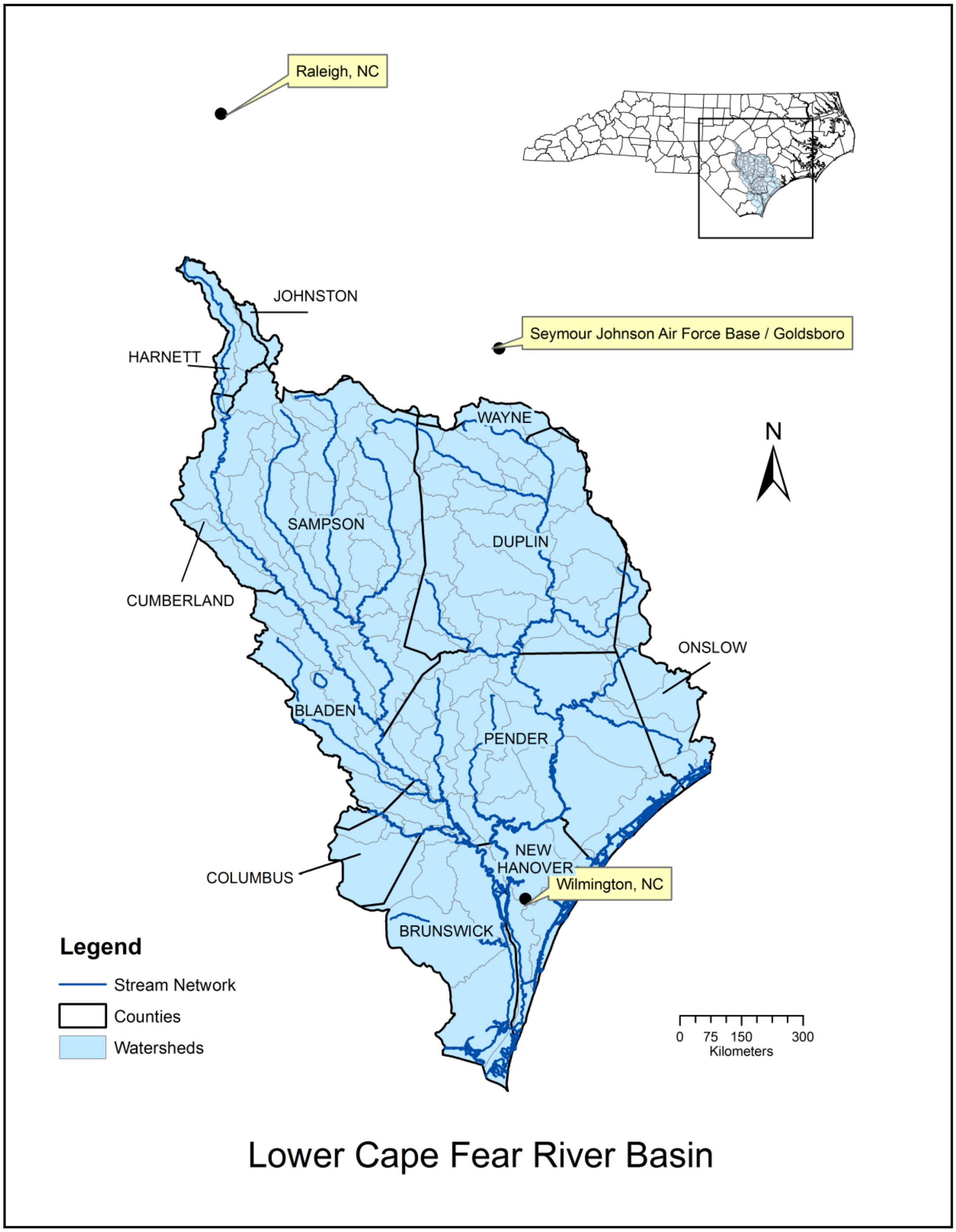

Raleigh, NC
JOHNSTON
HARNETT
Seymour Johnson Air Force Base / Goldsboro
WAYNE
N
SAMPSON
DUPLIN
CUMBERLAND
ONSLOW
BLADEN
PENDER
COLUMBUS
NEW HANOVER
Wilmington, NC
BRUNSWICK
Legend
Stream Network
Counties
Watersheds
0 75 150 300
Kilometers
Lower Cape Fear River Basin

Figure 1

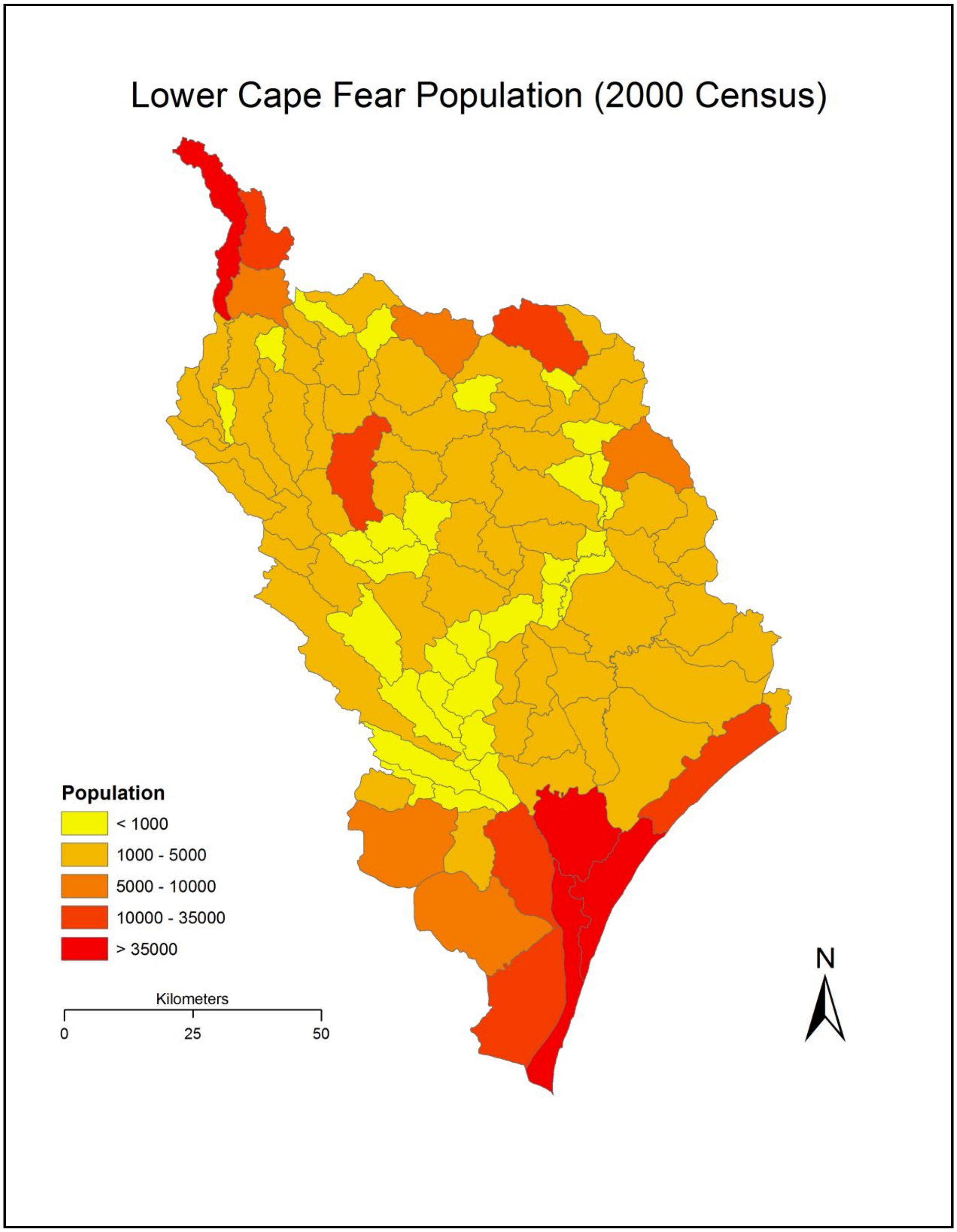

Lower Cape Fear Population (2000 Census)
Population
< 1000
1000 - 5000
5000 - 10000
10000 - 35000
> 35000
Kilometers
0
25
50
N

Figure 2

CHAPTER 4: METHODS AND ANALYSIS

The methodological approach for the analysis of the basin is described in detail here. Numerous tools were incorporated during the course of analysis. As such, the methodology is split into four primary steps. These steps consist of: 1. Data Collection, 2. Impervious Surface Analysis, 3. Water Balance Model Analysis, and 4. Water Stress Indicators Analysis. The result of a methodological approach such as this is a detailed assessment of both the current and future state of water resources in the study area. Before the analysis of the entire basin was undertaken, a detailed analysis of a single watershed in New Hanover County was examined to serve as a testing phase as well as an individual look at a densely populated watershed.

Data Collection

The data collection phase consists of gathering data essential to the implementation of vital tools such as the Impervious Surface Analysis Tool (ISAT) and the water balance model. In addition to these data, population data and watershed area are needed for the water stress analysis.

Data needed for the calculation of impervious surface cover consist of population density by block group and land cover data. The population density data are available from the US Census. Using the population by block group, population density is calculated within the Geographic Information System (GIS) software, ArcMap 9.3.The land cover used for this analysis was obtained from the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) (National Oceanic and Atmospheric Administration 2010). These datasets provide land cover data for the entire east coast of the United States up to the Piedmont. The population density data are available from the US Census. Using the population by block group, population density is calculated in ArcMap 9.3.

The Lower Cape Fear River Basin is comprised of 103 watersheds. Contained within and in close proximity to the basin lie nine weather stations. This extensive network of weather stations in the region is ideal for research of this nature. As a result of a network such as this, detailed analysis within the basin is achievable. However, techniques must be adapted in order to determine which watersheds correspond to the various weather stations.

The methodological approach utilized here is that of Thiessen polygons. According to Cooke and Mostaghimi (1992), the Thiessen method is “a weighted- average method in which the weight for each gauge is the proportion of the total area closer to it than to any other gauge”. Cooke and Mostaghimi (1992) incorporated methods such as kriging, inverse distance weighting, station average method, and the Thiessen method to interpolate gauge data. The results of their analysis showed little variance between methods for the case study they performed in Nomini Creek, Virginia (Cooke and Mostaghimi, 1992).

Numerous studies utilizing temperature and precipitation from multiple weather stations have incorporated the use of Thiessen polygon methodology. Tsakiris et al. (2007), who examine drought by incorporating a new Reconnaissance Drought Index (RDI) to be used in conjuction with the Standardized Precipitation Index (SPI), employ the use of Thiessen polygons in their analysis. Another study which demonstrates the use of Thiessen polygons in interpolating temperature and precipitation was completed by Shen et al. (2001). These and other studies show that a Thiessen polygon methodology is an accepted technique for interpolating temperature and precipitation.

Water balance analysis of the basin requires precipitation, temperature, and weather station location data. Nine weather stations are within or are in close proximity to the Lower Cape Fear River basin (Figure3). The locations of these stations are essential to splitting the basin into climate divisions utilizing the Thiessen polygon methodology. Historical precipitation (mm) and temperature (^{o}C) data were retrieved from the North Carolina State Climate Office and the United States Historical Climatology Network (USHCN),and are based on the 30 year climate normals for each station. The climate predictions were assessed to these normals to generate various climate change scenarios, which were derived from IPCC regional predictions. These scenarios include a best case, mean case, and worst case for each climate division.

The final phase in the data collection is for the water stress indicator analysis. Variables needed for this analysis consist of runoff, population, and area of each watershed within the basin. Runoff is retrieved from the output of the water balance in each scenario. The population is based on US Census block group data and is interpolated in ArcMap to reflect population by watershed. The area of each watershed is calculated in ArcMap using the “calculate geometry” function.

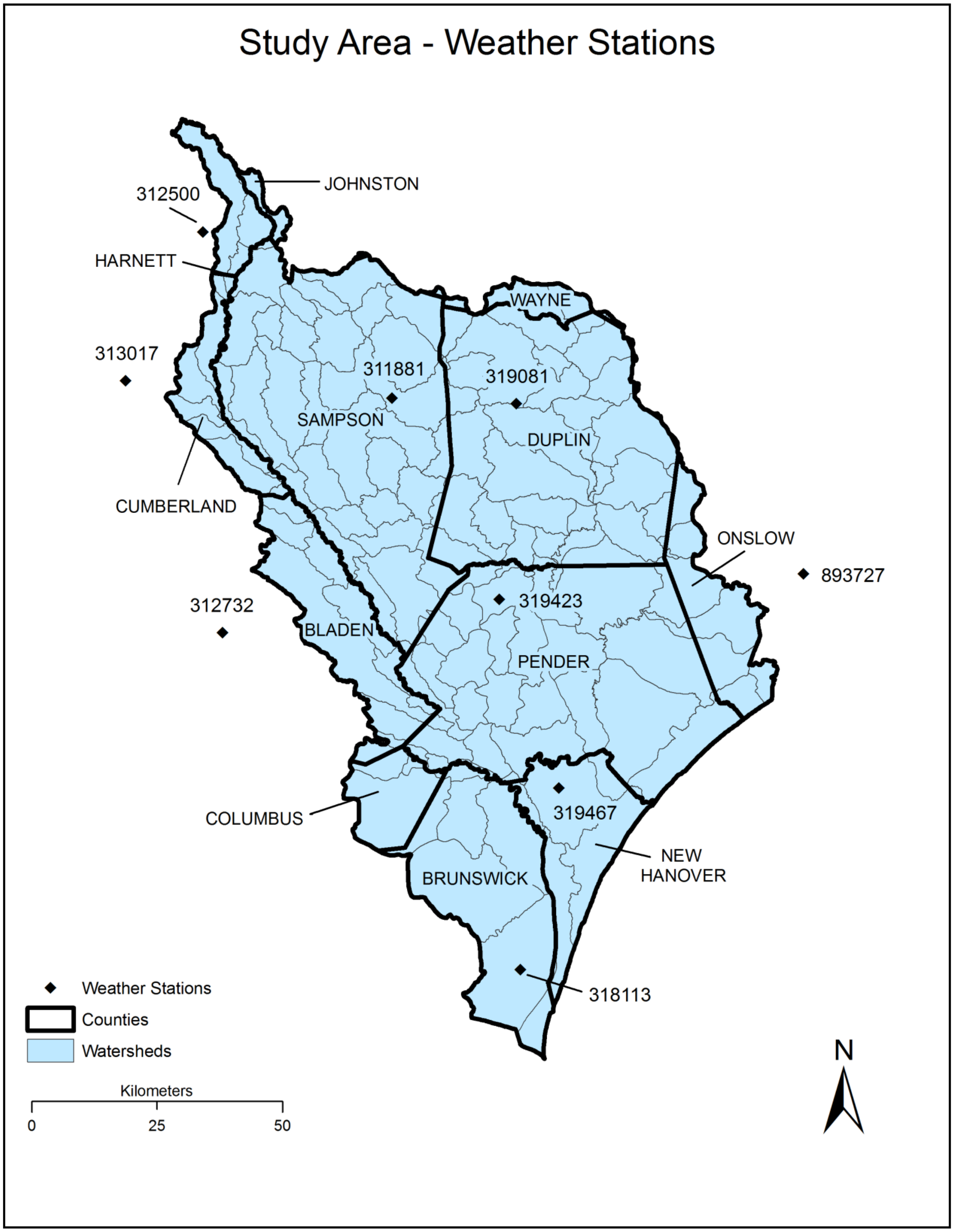

Study Area - Weather Stations
312500
JOHNSTON
HARNETT
313017
311881
319081
WAYNE
SAMPSON
DUPLIN
CUMBERLAND
ONSLOW
893727
312732
319423
BLADEN
PENDER
COLUMBUS
319467
NEW HANOVER
BRUNSWICK
318113
Weather Stations
Counties
Watersheds
Kilometers
0
25
50
N

Figure 3

Impervious Surface Analysis

The first step in this analysis was the estimation of impervious surfaces in the region. Impervious surfaces consist of any feature that inhibits precipitation from infiltrating the soil. These features include, but are not limited to, concrete, asphalt, and buildings. To achieve this, land cover data were retrieved from NOAA (C-CAP). In addition to the land cover data, GIS layers for watersheds and block groups were also utilized. Once the data were collected, each layer was opened in ArcMap 9.3. Once in ArcMap, the data were clipped to the boundaries of the study area. Once the data preprocessing phase was finished, the Impervious Surface Analysis Tool (ISAT) was used to assess the percent impervious in each watershed. This tool utilizes population density along with land cover data to estimate the percent impervious for each watershed. Built into ISAT are coefficients for each land type which are used to perform the calculation.

Basin analysis of impervious cover was calculated for 1996, 2001 and 2006. While 2006 was used for the baseline impervious cover in each watershed, trends found in the 1996 to 2006 impervious cover were extrapolated out to estimate future impervious cover. The impervious cover values were then extrapolated to the year 2100, in order to match the climate predictions. A linear extrapolation for the entire basin was utilized due to the fact that impervious cover remained fairly constant across the basin. Certain areas which show substantial change, such as New Hanover County, could be examined individually to get a more detailed look as to the impact of impervious cover on water availability. This analysis allows for each watershed to have a unique attribute in addition to the precipitation, temperature, and soil moisture capacity. The result is a detailed analysis of each watershed thatcan illustrate which areas need to address the issue of impervious cover as a step in sustaining future populations' water needs.

Water Balance Modeling and Falkenmark Indicators

The primary model utilized in the basin is based on the USGS Thornthwaite model (1948). The first step in the process was to program the model into Matlab , which allowed for a customization of the model. Certain aspects of the original Thornthwaite model (1948) were not needed in this analysis, such as snow melt, and were thus eliminated from the model. Specific equations can be found on the USGS website (United States Geological Survey 2010). After the model was programmed into Matlab, testing commenced. For testing, the model was set to run similarly to that of the original Thornthwaite model (1948), so one watershed was analyzed at a time. Thus, the same input file was used in the original model and the new model in Matlab. The results were then compared for consistency between the models. The output from the models matched, and it was concluded that the model was working correctly.

While the original model could only analyze one watershed at a time, the next step in the methodological process was to automate the Matlab model. In contrast to the original Thornthwaite model, this process allowed for analysis of all 103 watersheds in the basin with one run. This automated model consisted of two input files, a watershed climate and a watershed information file. The following outlines the processes utilized in constructing these files.

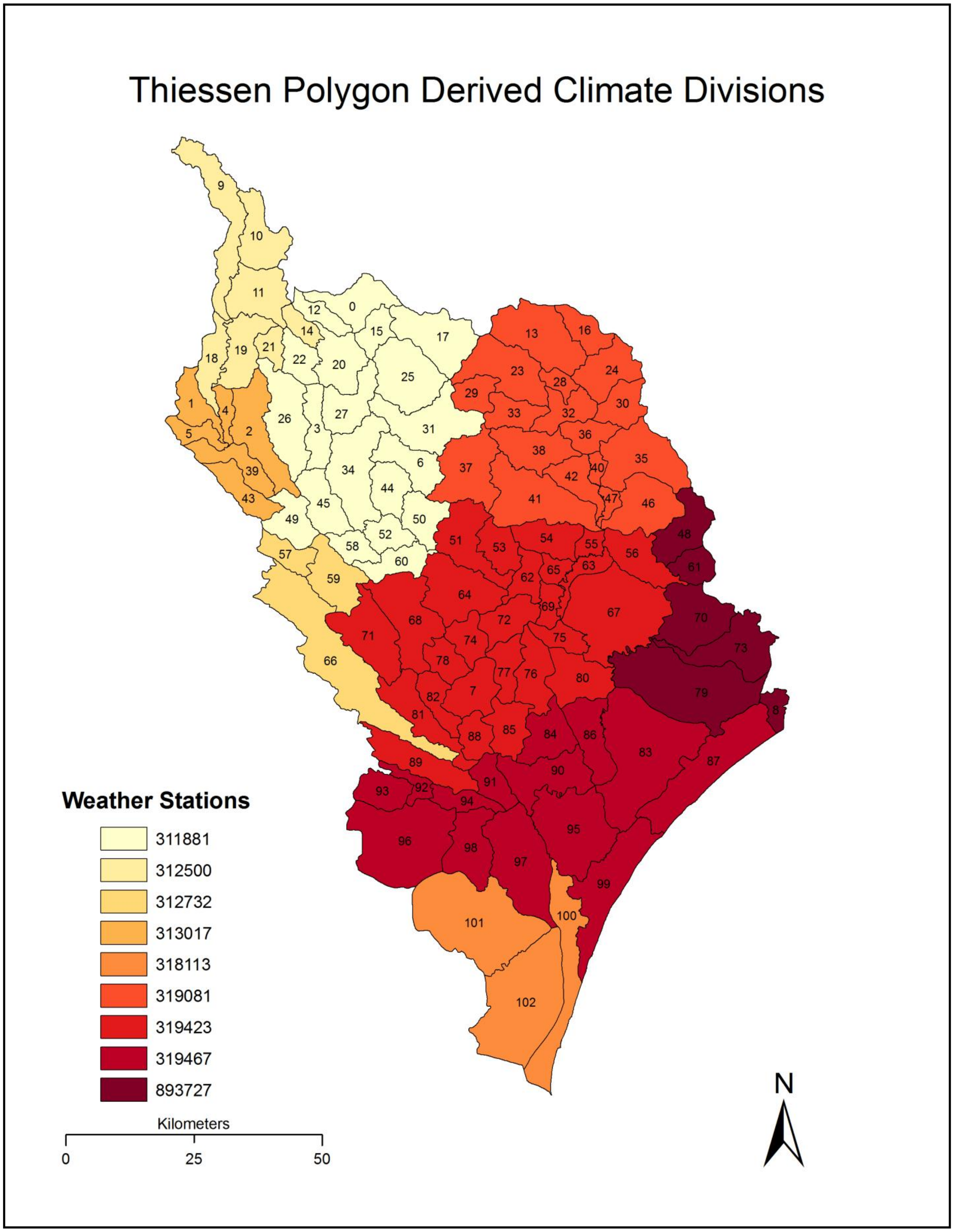
The climate files, which are the meteorological input files to the model, were constructed based on the climate division in the basin, which are a product of Thiessen polygon interpolation carried out in ArcMap 9.31. There are nine climate divisions which correspond to the nine weather stations (Figure 4). The baseline climate file has the climate normals (30 year averages) for each weather station. In addition to the base climate file, climate files corresponding to IPCC best case, mean case, and worst case predictions were created. The scenarios retrieved from the

IPCC are regional predictions for the Southeast United States and were not downscaled any further to the basin study area. Table 2 illustrates the values of the three climate scenarios. The best case scenario reflects the highest increase in precipitation and the lowest increase in temperature, while the worst case prediction is the opposite, with high increases in temperature and decreases in precipitation in every season except for winter.The data in these files are called in the model based on the data provided in the watershed information file.

Construction of the watershed information files consisted ofadditional steps. The data provided in these files are: 1. watershed ID, 2. climate division, 3. soil moisture capacity, and 4. impervious cover. Two watershed information files were created. The first file consisted of impervious cover for 2006, while the second utilized extrapolated impervious cover. The climate division to which each watershed belonged was determined by displaying the watersheds in ArcMap with the unique ID labeled and the climate divisions overlaid. The next step was to determine the soil moisture capacity of each watershed, which is a parameter that needs to be set for the model and is based largely on the soil type within the watersheds. This was achieved by overlaying a global soil moisture dataset, retrieved from Batjes(2000), which allowed for a rather detailed look at the soil moisture capacity across the basin.

Table 1

Climate Scenarios (IPCC)						
Season	**Scenarios**					
	Best Case		**Mean Case**		**Worst Case**	
	Precipitation	*Temperature*	*Precipitation*	*Temperature*	*Precipitation*	*Temperature*
Winter	28%	2.1 °C	11%	3.8 °C	2%	6 °C
Spring	23%	2.3 °C	12%	3.5 °C	-4%	5.9 °C
Summer	13%	2.1 °C	1%	3.3 °C	-17%	5.4 °C
Fall	17%	2.2 °C	7%	3.5 °C	-7%	5.7 °C


Thiessen Polygon Derived Climate Divisions
Weather Stations
311881
312500
312732
313017
318113
319081
319423
319467
893727
Kilometers
0
25
50
N
9
10
11
12
0
15
17
14
13
16
21
19
22
20
18
25
23
28
24
29
1
4
26
27
3
2
31
33
32
30
5
36
38
35
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81
8
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93
92
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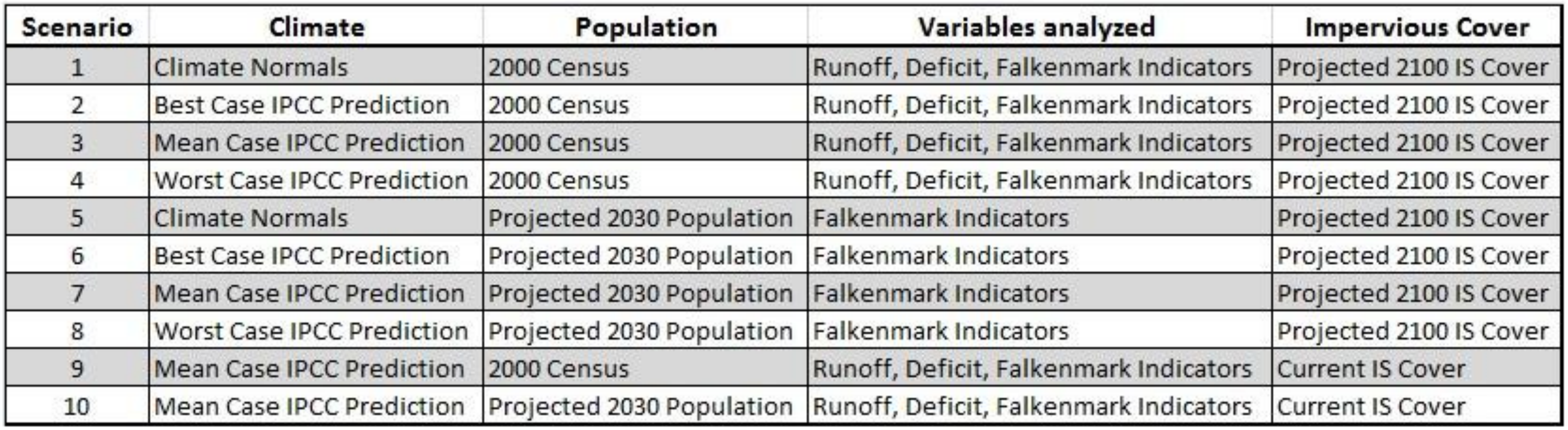
96
98
97
99
100
101
102

Figure 4

This is the best attainable soil moisture capacity data without actually going into the field and taking samples throughout the basin.

At this point, the water balance analysis of the entire basin was performed. Various scenarios were run in order to assess the state of water resources (Table 3).Output from these scenarios including runoff, yearly deficit, and soil moisture provide insight into the current state of water resources in the region as well as a range of possibilities for future water resource levels.

The last step in the analysis of water resources in the basin and perhaps the most telling was the Falkenmark water stress analysis. This analysis was undertaken in ArcMap, utilizing runoff values from the water balance model. The Falkenmark indicators provide insight as to whether the water in the basin is adequate to meet the demands of the population. Therefore the only variables needed to do the calculation are the available water (runoff output from the model), area of the watershed (calculated in ArcMap), and population (US Census). As the Falkenmark indicators are a function of available water and population, scenarios incorporating current population and predicted population values were utilized. The projected population was retrieved from US Census projections.



Scenario	Climate	Population	Variables analyzed	Impervious Cover
1	Climate Normals	2000 Census	Runoff, Deficit, Falkenmark Indicators	Projected 2100 IS Cover
2	Best Case IPCC Prediction	2000 Census	Runoff, Deficit, Falkenmark Indicators	Projected 2100 IS Cover
3	Mean Case IPCC Prediction	2000 Census	Runoff, Deficit, Falkenmark Indicators	Projected 2100 IS Cover
4	Worst Case IPCC Prediction	2000 Census	Runoff, Deficit, Falkenmark Indicators	Projected 2100 IS Cover
5	Climate Normals	Projected 2030 Population	Falkenmark Indicators	Projected 2100 IS Cover
6	Best Case IPCC Prediction	Projected 2030 Population	Falkenmark Indicators	Projected 2100 IS Cover
7	Mean Case IPCC Prediction	Projected 2030 Population	Falkenmark Indicators	Projected 2100 IS Cover
8	Worst Case IPCC Prediction	Projected 2030 Population	Falkenmark Indicators	Projected 2100 IS Cover
9	Mean Case IPCC Prediction	2000 Census	Runoff, Deficit, Falkenmark Indicators	Current IS Cover
10	Mean Case IPCC Prediction	Projected 2030 Population	Runoff, Deficit, Falkenmark Indicators	Current IS Cover

Table 3 -Model Scenarios

CHAPTER 5: LOWER CAPE FEAR RESULTS

Results of this research are twofold. The first is the results of the initial testing phase of the analysis. These results illustrate the functionality of the methodology while also providing a detailed analysis of one watershed in New Hanover County. Following the results of the testing phase are the results for the larger scale analysis, which examines the entire basin.

Water Balance Testing

In order to test the process which will be utilized for this research, a small case study was undertaken. For the purposes of illustration, a single watershed in New Hanover County, which is located in the lower Cape Fear River basin, was analyzed. Figure 5 is a depiction of the study area for this demonstration case study.   Impervious surface analysis is the initial phase of the test and the results are depicted in the Figure 6 map which shows that the watershed is 6.45% impervious.

Following calculation of the impervious surface, the climatological variables were retrieved. The precipitation and temperature data spanned from 1978 through2008 and were retrieved from the U.S. Historical Climatology Network station 318113, which is the closest station to the study site. To get a baseline of how impervious surfaces and climate change impact runoff, various scenarios based on these data were run through the USGS Thornthwaite (1948) monthly water balance model. Temperature and precipitation are direct inputs to the model, while impervious surfaces are accounted for through the direct runoff fraction coefficient. These

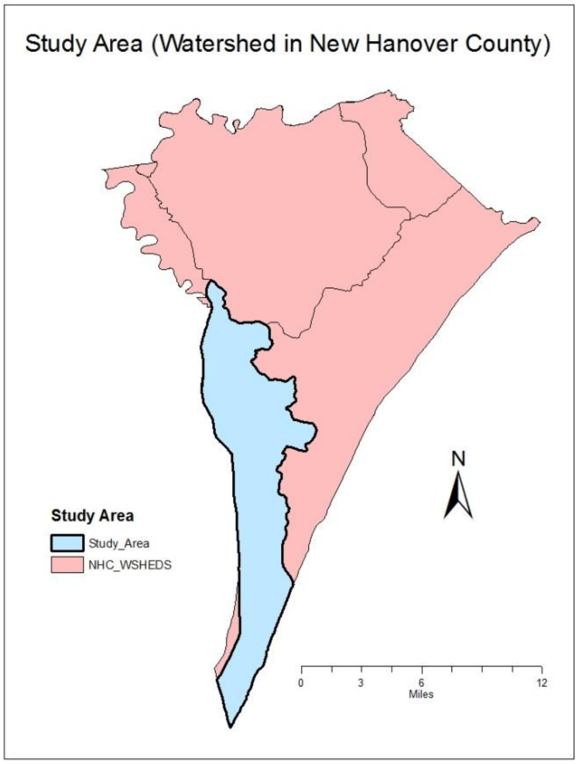


Figure 5

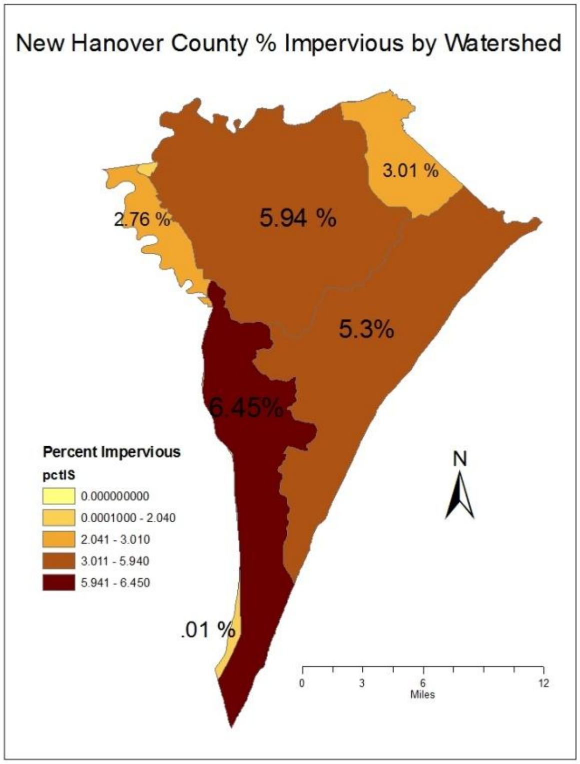


Figure 6

scenarios consisted of: 1.observed climate averages from 1977 through 2008 under natural conditions (no impervious surfaces); 2. observed climate averages from 1977 through2008 with 6% of the watershed impervious; 3.a 5% increase in precipitation and temperature under natural conditions; and 4.a 5% increase in precipitation and temperature with 6% of the watershed impervious. Output from this model allows for an assessment of future water resources in a variety of ways. First and most obvious is runoff. Looking at the variation of runoff under current conditions along with predictions provides some insight into how runoff or the availability of water is affected. Figure 7 illustrates the average yearly runoff in millimeters for each of the four scenarios. The output from the water balance varied in yearly runoff from about 419 mm to 443 mm based on the four scenarios, withthe scenario with 6 % impervious and a 5 %

increase in precipitation and temperature producing the highest values. Other important factors are soil moisture, water deficit and evapotranspiration. Evapotranspiration is as important a consideration for water resources as temperature and precipitation. This model incorporates the Hamon (1961) equation to estimate potential evapotranspiration and, based on that, actual evapotranspiration is determined.

Equation 2

$$PET_{Hamon} = 13.97 * d * D^2 * W_t$$

$$W_t = 4.95 * e^{0.062 * T} / 100$$

d = # of days in month

D = Avg hours of daylight in month

W_t = Saturated water vapor

With known soil moisture, deficit, precipitation, and evapotranspiration, climatograms can be produced that illustrate how the overall water resources will be affected by changes in climate or impervious surfaces. While precipitation may increase for the region under a warming climate, the seasonal distribution will likely be altered which can extend the yearly deficit. Climatograms are a good tool for looking at the seasonal impact of climate change and impervious surfaces.

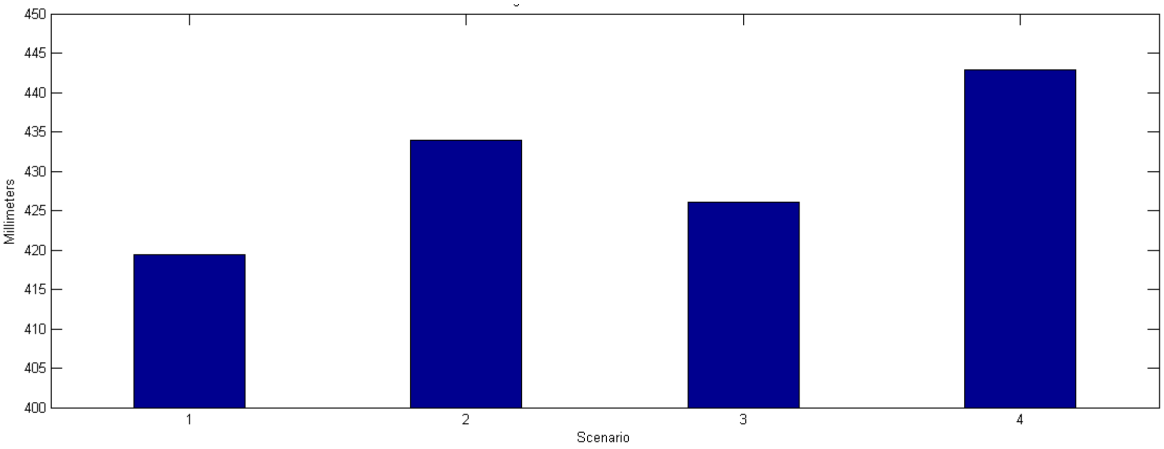


Figure 7. Average Annual Runoff for Each Scenario

With the output from the USGS Thornthwaite (1948) monthly water balance model, climatograms were produced for each scenario (Figures 8-11). Variables include precipitation, runoff, potential evapotranspiration (PET), actual evapotranspiration (AET), and soil moisture. Although the graphs look similar at first glance, there are differences in runoff, soil moisture, and yearly deficits as the climate changes. Deficit is illustrated with these graphs by the difference between PET and AET (PET – AET). PET – AET is an important variable as it indicates when water is being recharged (PET < AET) and when it is being depleted (PET > AET). As yearly deficits rise, this could be an indication of decreased rainfall, or rainfall could be remaining constant or even increasing, but warmer temperatures are increasing the evapotranspiration. The climatogram with a natural landscape (no impervious surfaces) and the observed climate data shows that the deficit period starts around late May and extends until mid August (Figure 8). For the scenario with 6% impervious surface, the deficit increases and soil moisture decreases (Figure 9). The increase in the deficit is likely due to the decrease in soil moisture, which causes a decrease in actual evapotranspiration. The scenario featuring a natural landscape with a 5% increase in temperature and precipitation (Figure 10) indicates a more intense deficit than the natural landscape in Figure 8, meaning that even with more precipitation, the deficit increases, due to the effect of rising temperature. The final scenario, that of 6% impervious surfaces and a 5% increase in precipitation and temperature, produced the highest deficit and the lowest soil moisture (Figure 11).

The lowest soil moisture levels reached in each scenario are shown in Table 4. Just a 5% increase in the temperature and precipitation had a substantial impact on the output of the model in both scenarios featuring the increase, with scenario 3 decreasing the lowest at 9.5 percent and scenario 4 decreasing 22.4 percent. Research, such as that conducted by Robinson (2006) in North Carolina, showed the possibility of climate induced changes in seasonality decreasing summer precipitation by as much as 10 %,which could increase the deficit for the region. The differences between scenarios, while subtle in some cases, are apparent and can influence the availability of water. Table 5 illustrates the fluctuations in the deficit (PET-AET) for each scenario. A natural landscape with observed climate data produced a yearly deficit of 8.4mm. Under the same climatic conditions but with 6% impervious cover, the deficit increased by 7mm to 15.4mm. The climate change scenario had a similar impact, although not as substantial as the addition of impervious surfaces. A 5% increase in precipitation and temperature enhanced the deficit by 4.3mm, bringing the total deficit to 12.7mm. Finally, the scenario featuring 6% impervious area along with a 5% increase in the climate variables produced the greatest deficit. This scenario produced a deficit of 21.4mm, an increase of 13mm (155 % increase) from natural conditions.

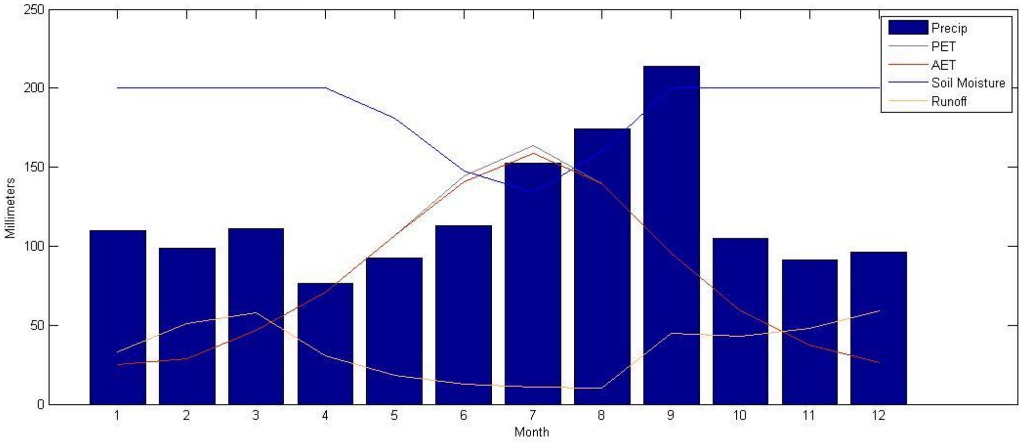


Figure 8.Climatogram - Natural Landscape with Historical Climate,(1978-2008)

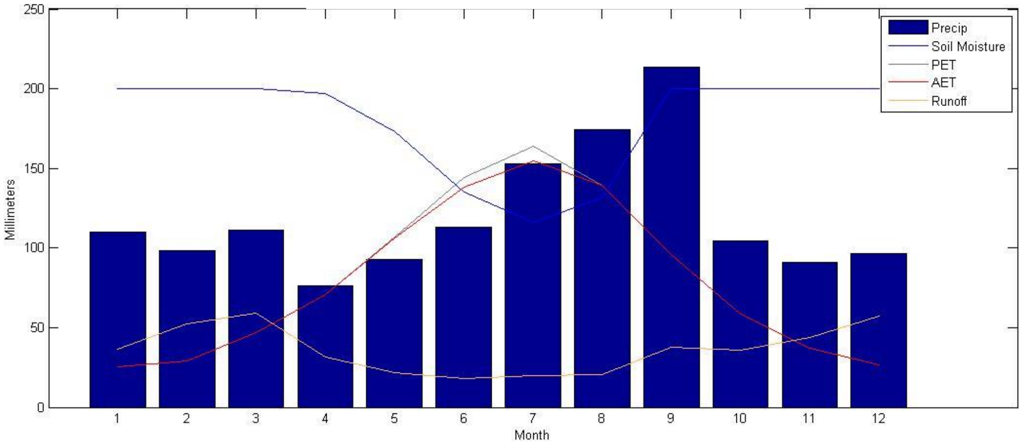


Figure 9.Climatogram – 6% Impervious, Historical Climate

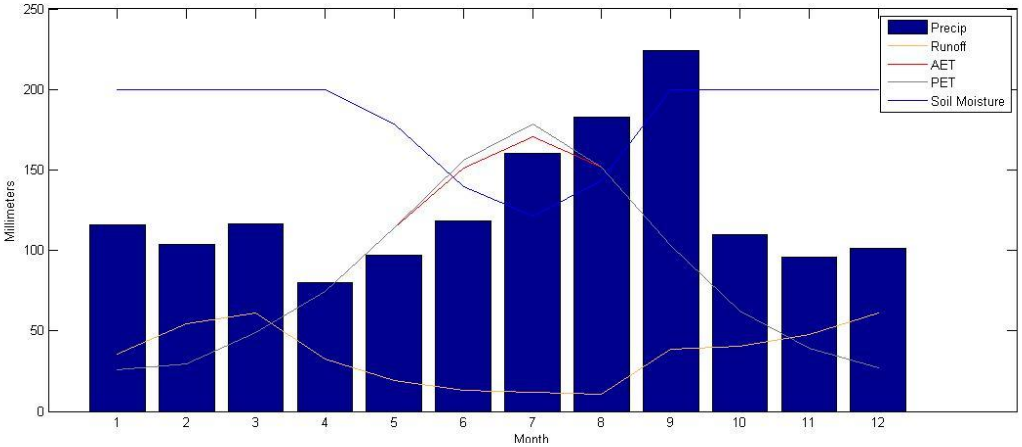


Figure 10.Climatogram – Natural Landscape with 5% Increases in Precip and Temp

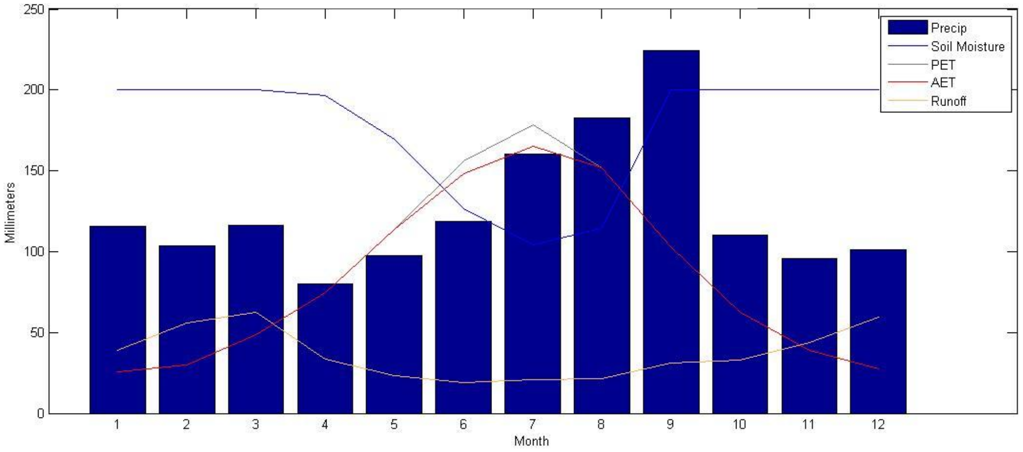


Figure 11.Climatogram – 6% Impervious and 5% Increase in Precip and Temp

Lowest Montly Soil Moisture for Each Scenario (millimeters, %)			
Scenario	**Minimum Soil Moisture**	**% Change**	**Month**
Natural Landscape - Observed Climate	133.9	-	July
6% impervious - Observed Climate	116.4	-13.07	July
Natural Landscape - 5% Increase Climate	121.2	-9.50%	July
6% Impervious - 5% increase Climate	103.9	-22.40%	July

Table 4

Summary Table - Yearly Deficits (PET-AET) for the Four Scenarios (millimeters)				
Scenario	**May**	**June**	**July**	**Total**
Natural Landscape - Observed Climate	0.000	3.500	4.900	8.400
6% impervious - Observed Climate	0.400	5.900	9.100	15.400
Natural Landscape - 5% Increase Climate	0.000	4.700	8.000	12.700
6% Impervious - 5% increase Climate	0.500	7.700	13.200	21.400

Table 5

As is evident from these results, prolonged deficits caused by climate change and impervious surfaces could present problems in the future, especially when increasing demand is taken into account. The example case study in New Hanover County demonstrates the influence that impervious cover has on water resources. Six percent impervious surface in the watershed increased the deficit by 7mm. The impact of climate change on the local hydrology is also undeniable. The 5% increase in climatic variables, which did not take into account changes to seasonality, produced a 4.3mm increase in yearly deficit. Recent droughts in the region have shown that the area is not immune to water resource issues. This study attempts to predict what future conditions may be, so measures can be taken to prepare for what lies ahead.

The methods used here to demonstrate the process of utilizing a water balance to predict future conditions is the framework for the analysis of the Lower Cape Fear River basin. The 5% increase in precipitation and temperature is an arbitrary value used just for the purposes of illustration. The values for the Lower Cape Fear basin are based on assessment of published seasonal climate predictions for this region. The use of seasonal changes will allow the model to assess shifts in seasonality, in addition to addressing the total fluctuations in precipitation and/or temperature. A shift in the distribution and intensity of precipitation can have a substantial impact on water resources or the yearly deficit. Previous research suggests that the southeast United States will experience an increase in yearly precipitation, but the distribution and intensity will be altered (Arnell 1999, Hurd et al. 1999, Robinson 2006). Water stress indicators are established based on demand and availability under future conditions. This provides insight as to whether availability will meet demands. If demands are not met, infrastructure needs to be put in place to sustain water resources.

Impervious Cover in the Lower Cape Fear

The impervious cover in the basin remained fairly constant from 1996 to 2006,although some areas showed substantial growth. Watersheds with the most growth lie within New Hanover County. This is not surprising given that New Hanover County is home to Wilmington North Carolina, the largest city in the study area. The impervious cover in 1996 is depicted in Figure 12. Figure 13 is a depiction of the 2006 ISAT calculated impervious cover for the basin, the values that are used as the baseline for impervious cover in the study areabecause of the availability of land cover data. As can be seen in both maps, the New Hanover County area has the highest values in impervious cover as well as the highest growth rates. Based on the output from this analysis, the impervious cover was extrapolatedto reflect impervious cover in 2100(Figure 14).These predicted values are used in conjunction with the climate predictions to estimate future water resource conditions.There is a surprisingly slow growth in impervious cover in the basin, which suggests that the impact from impervious cover may not be substantial.

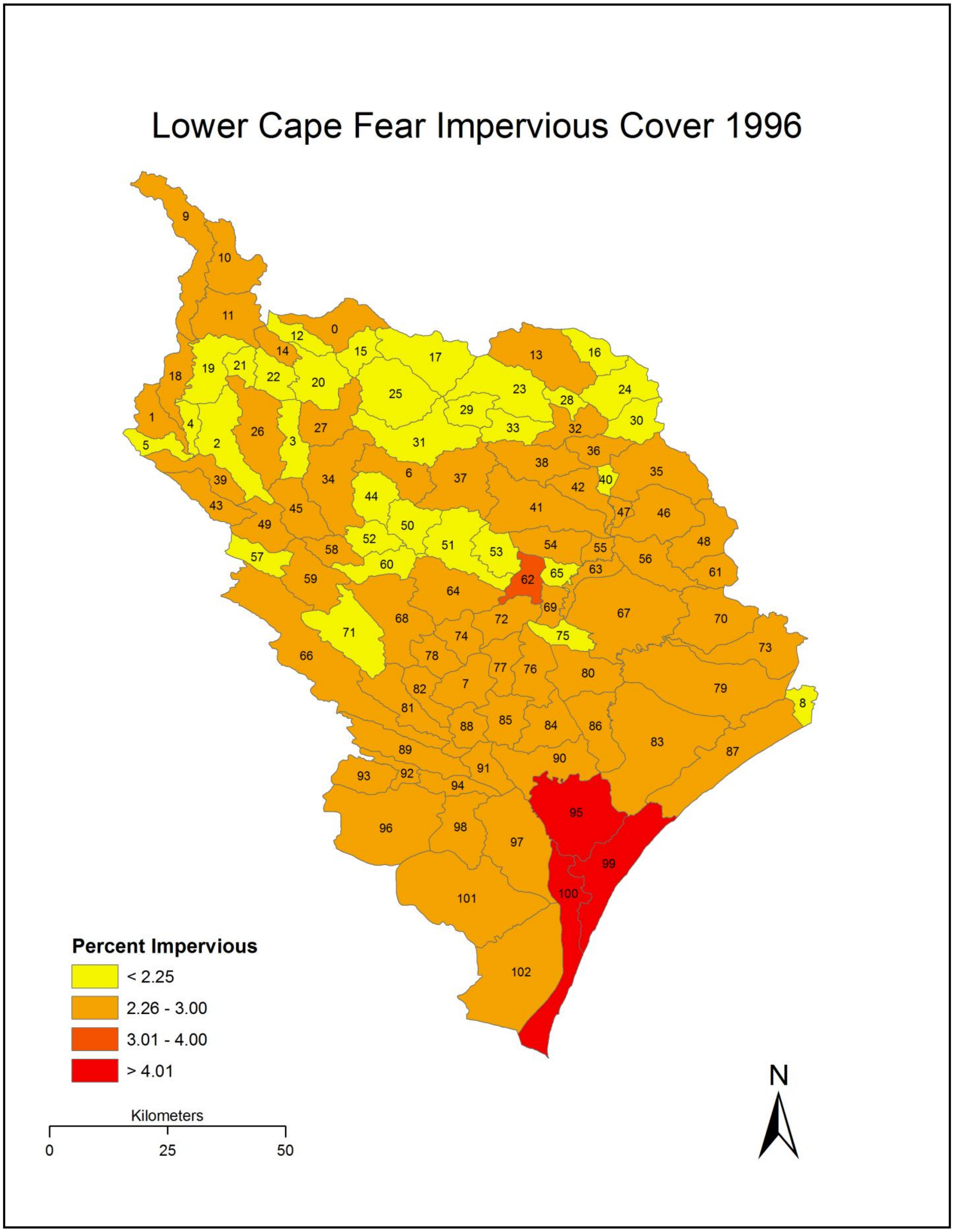
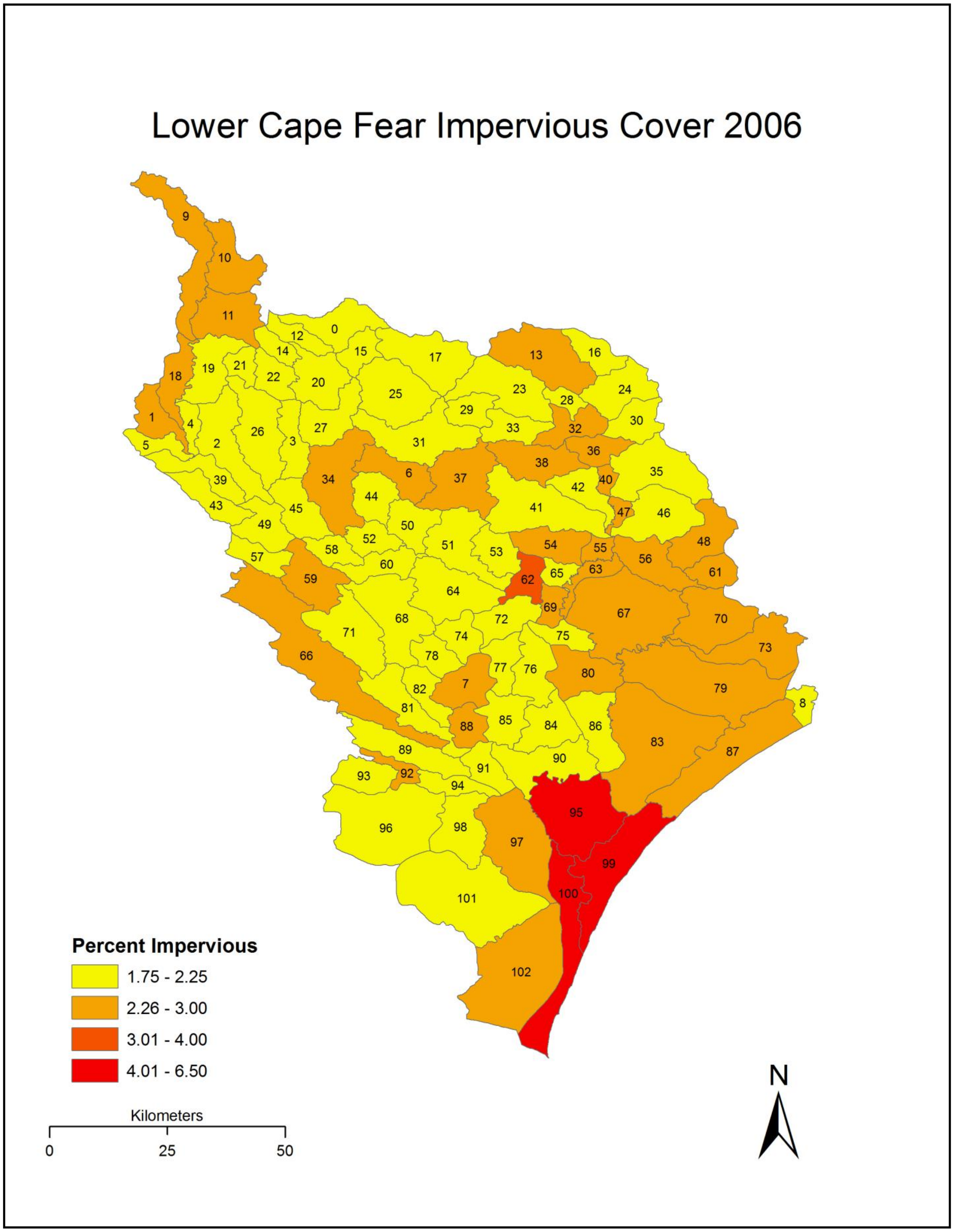

Lower Cape Fear Impervious Cover 1996

Figure 12


Lower Cape Fear Impervious Cover 2006
9
10
11
0
12
14
15
17
13
16
18
19
21
22
20
25
23
24
28
1
4
2
26
3
27
29
33
32
30
5
31
36
34
6
37
38
35
39
40
42
43
44
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81
8
88
85
84
86
89
83
87
90
91
93
92
94
95
96
98
97
99
100
101
102
Percent Impervious
1.75 - 2.25
2.26 - 3.00
3.01 - 4.00
4.01 - 6.50
Kilometers
0
25
50
N

Figure 13

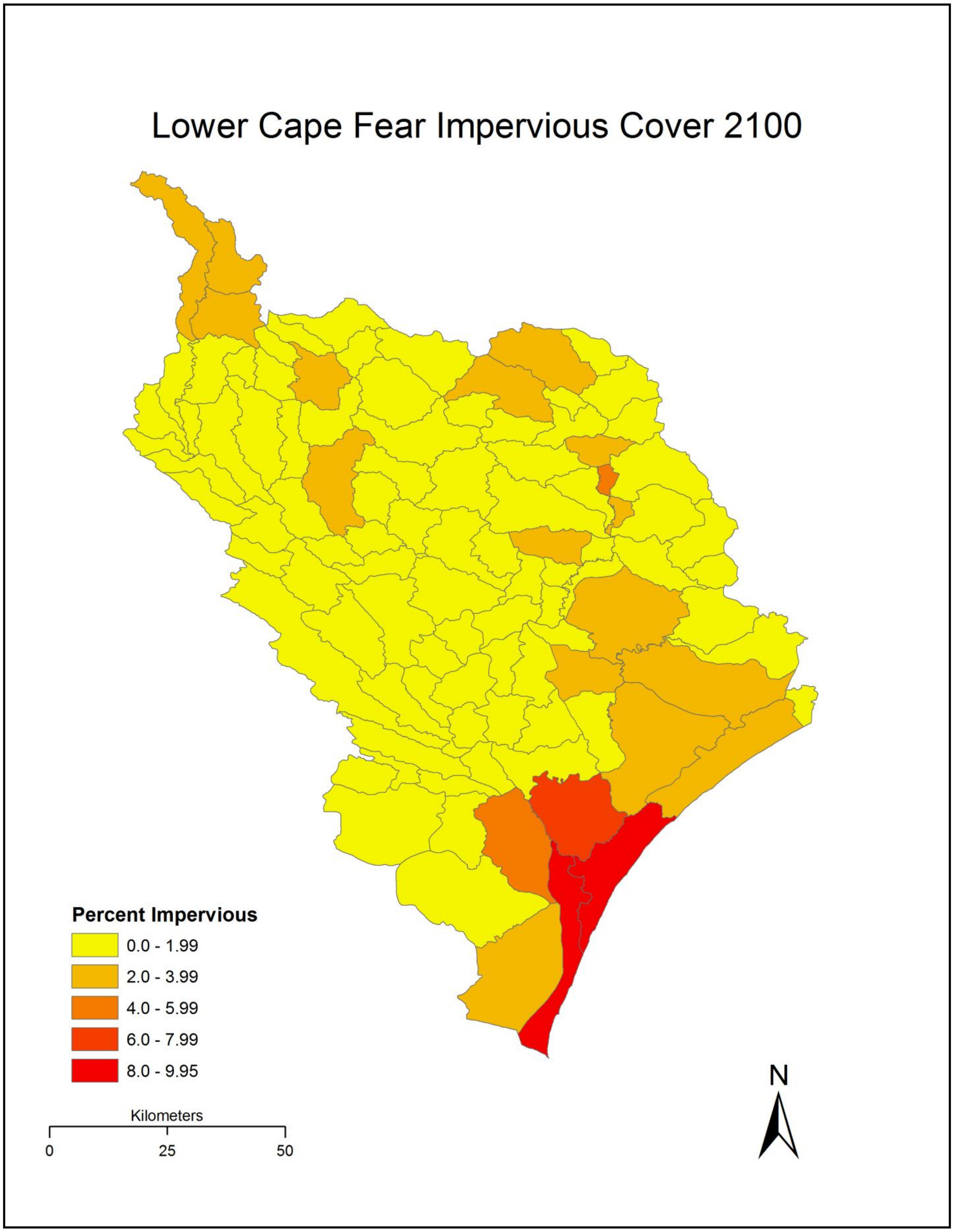
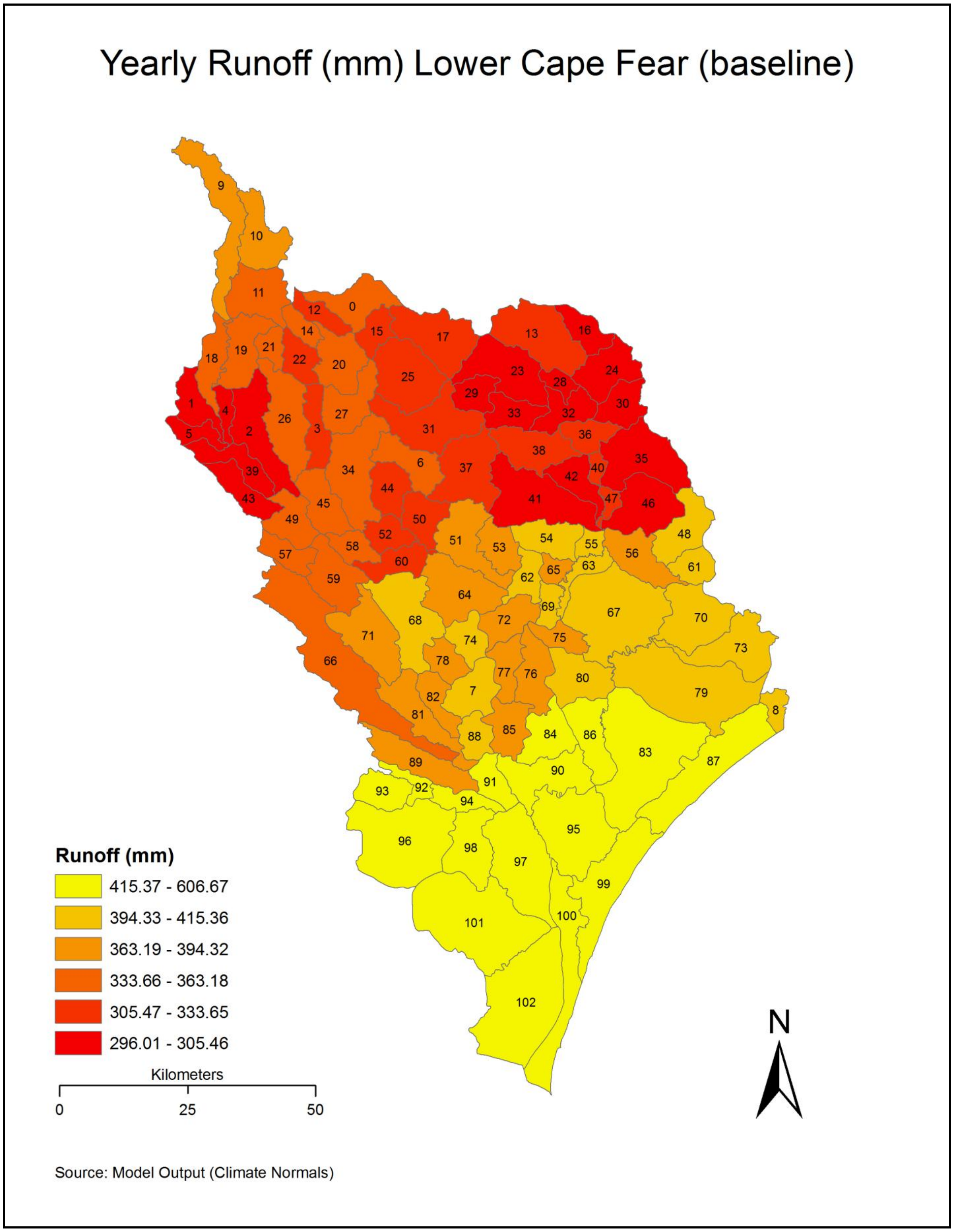

Lower Cape Fear Impervious Cover 2100
Percent Impervious
0.0 - 1.99
2.0 - 3.99
4.0 - 5.99
6.0 - 7.99
8.0 - 9.95
Kilometers
0
25
50
N

Figure 14

Water Balance Results

The first run in the water balance analysis was for the baseline conditions, incorporating the climate normals and the 2006 impervious cover. Figure 15 is a depiction of the runoff for the base scenario. Maps for each scenario depicting runoff were generated and can be seen in Appendix A.

The distribution of runoff or water availability in the Lower Cape Fear River basin (Figure 15) varies substantially by watershed. The overall trend shows high values for runoff in the southern basin, decreasing in watersheds to the North, with the lowest values showing up in Duplin and Cumberland Counties. The distribution of runoff values for each scenario can be found in Appendix A. The change in runoff from the baseline to the best case scenario(Figure16) depicts a similar pattern as Figure15, butthe runoff in the basin increases in this scenario. However, the extent of the increase varies throughout the basin. The regions which produced the least amount of runoff in the baseline scenario (Figure 15) increased the least in this scenario. While the water availability increased in the best case scenario (Figure 16), runoff values decreased for the entire basin in the mean case scenario (Figure 17). The central watersheds are showing the biggest decrease in available water, which could play a role in increasing the risk of water stress in the region. The difference in the baseline to worst case IPCC prediction (Figure18) is substantial throughout the basin. However, the values in the southern watersheds surrounding New Hanover County indicate drastic decreases in water availability (runoff), by as much as 50%. This could present problems in the future as population is growing rapidly in and around New Hanover County.


Yearly Runoff (mm) Lower Cape Fear (baseline)

Source: Model Output (Climate Normals)

Figure 15

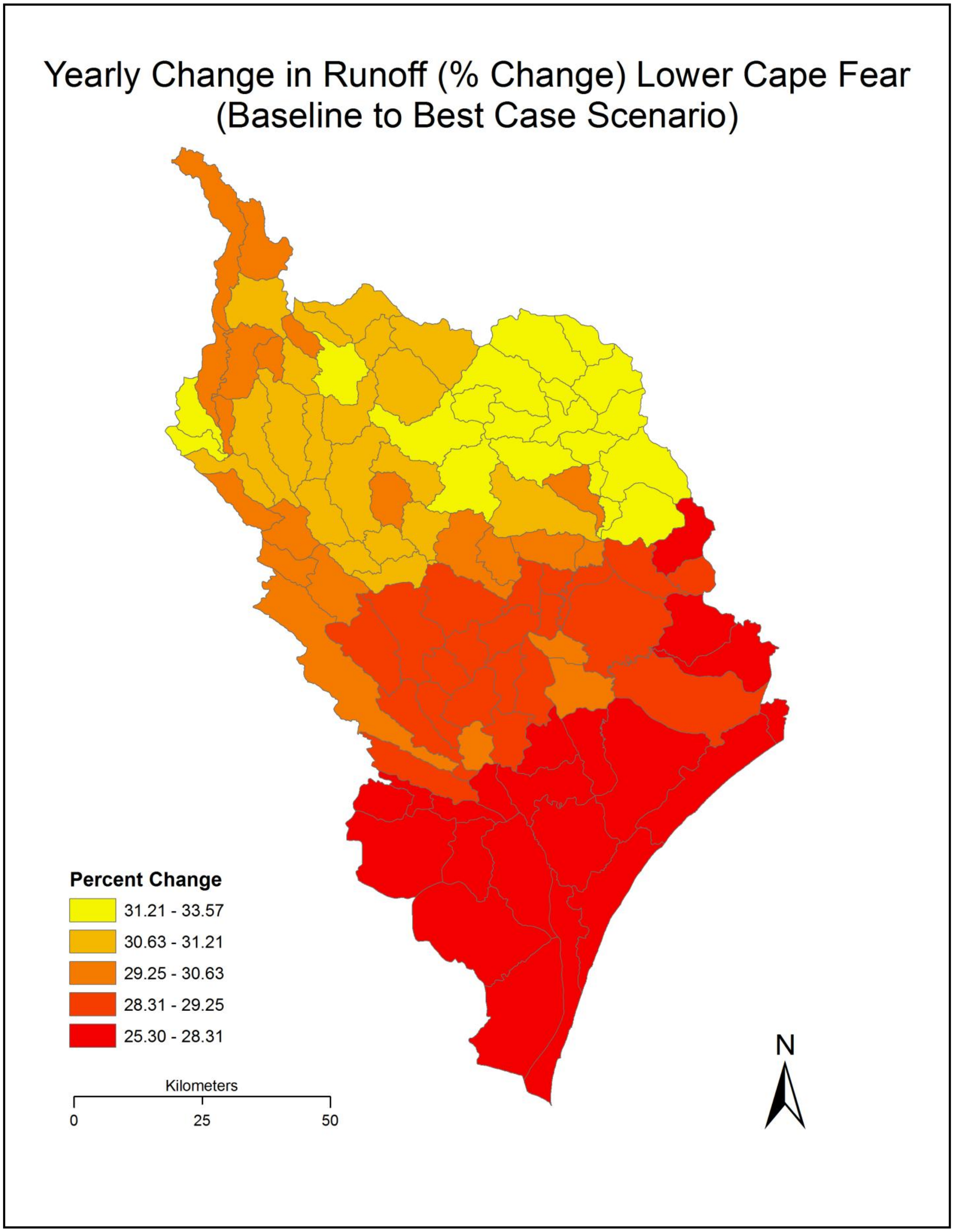
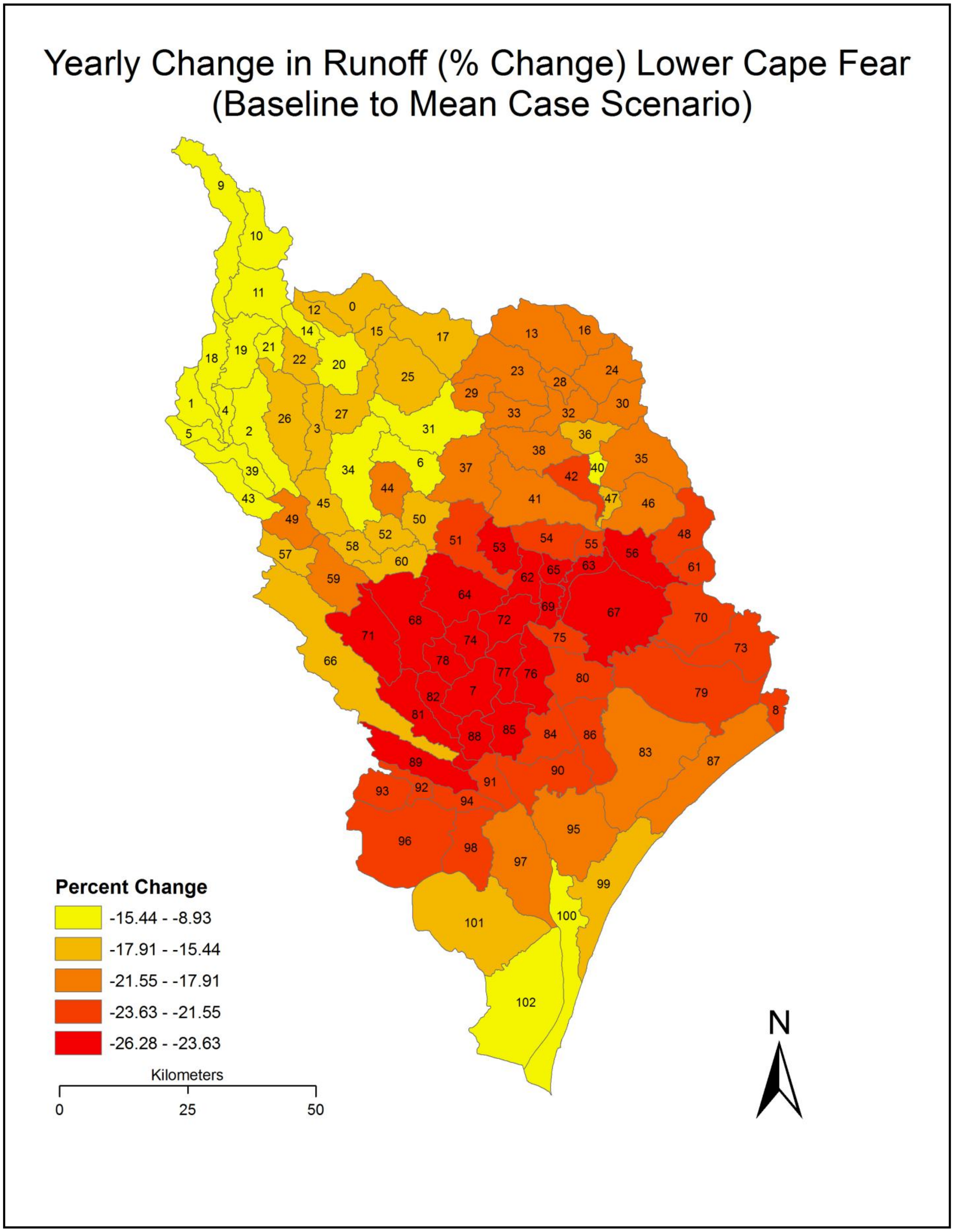

Yearly Change in Runoff (% Change) Lower Cape Fear
(Baseline to Best Case Scenario)
Percent Change
31.21 - 33.57
30.63 - 31.21
29.25 - 30.63
28.31 - 29.25
25.30 - 28.31
Kilometers
0
25
50
N

Figure 16


Yearly Change in Runoff (% Change) Lower Cape Fear
(Baseline to Mean Case Scenario)
9
10
11
12
0
14
15
17
13
16
19
21
22
20
18
25
23
24
28
29
1
4
26
27
33
32
30
5
2
3
31
36
38
37
6
34
35
39
42
40
43
44
41
47
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45
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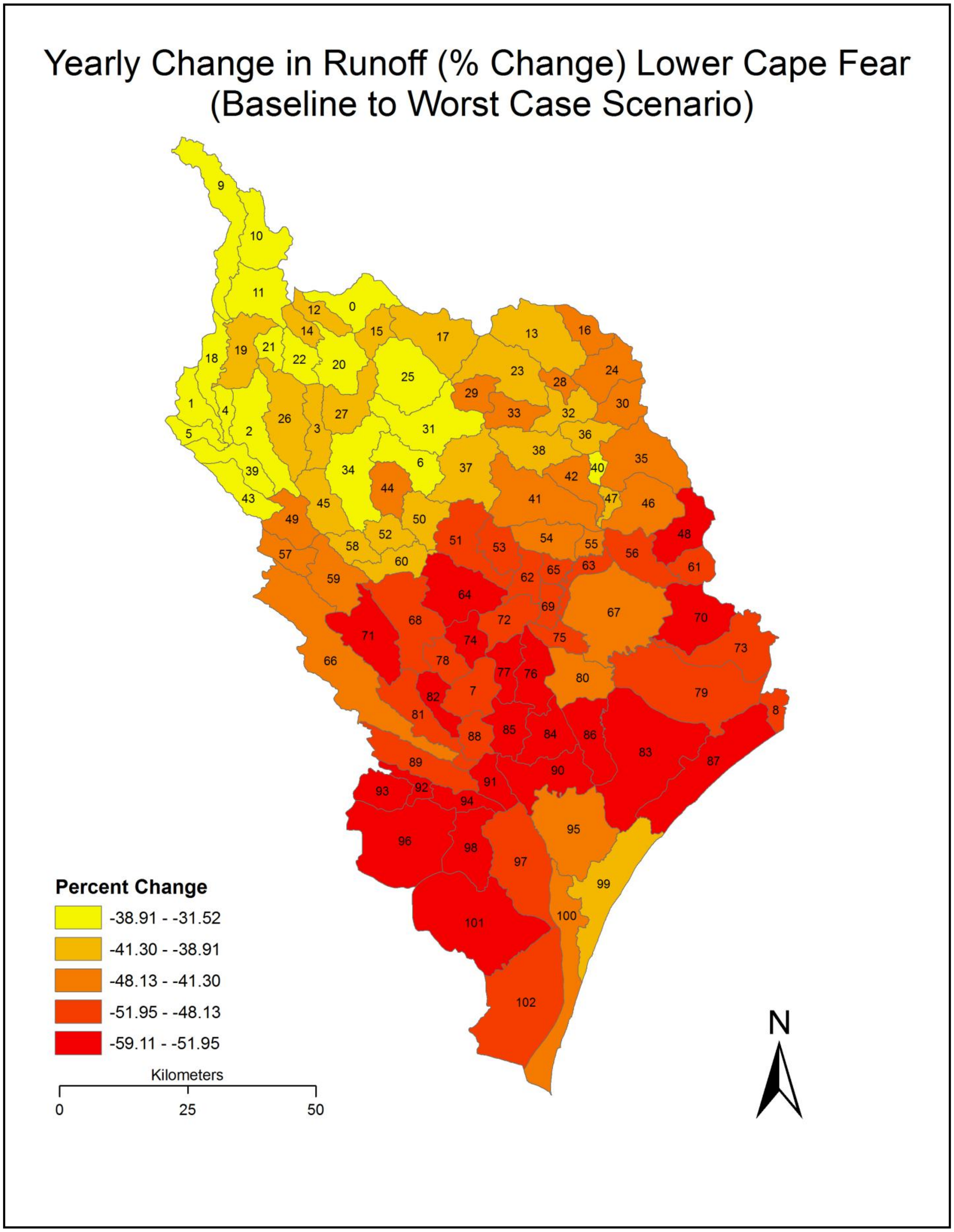
69
67
68
70
72
71
74
75
73
66
78
77
76
80
7
79
82
81
8
85
88
84
86
83
89
87
90
91
92
93
94
95
96
98
97
99
100
101
102
Percent Change
-15.44 - -8.93
-17.91 - -15.44
-21.55 - -17.91
-23.63 - -21.55
-26.28 - -23.63
Kilometers
0
25
50
N

Figure 17


Yearly Change in Runoff (% Change) Lower Cape Fear
(Baseline to Worst Case Scenario)
9
10
11
12
0
14
15
17
13
16
19
21
18
22
20
25
23
24
28
29
1
4
27
33
32
30
26
3
31
5
2
36
38
35
39
34
6
37
40
42
44
43
45
41
47
46
49
50
48
52
51
54
55
58
53
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69
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70
68
72
71
74
75
73
78
66
77
76
80
7
79
82
8
81
88
85
84
86
83
87
89
90
91
93
92
94
95
96
98
97
99
100
101
102
Percent Change
-38.91 - -31.52
-41.30 - -38.91
-48.13 - -41.30
-51.95 - -48.13
-59.11 - -51.95
Kilometers
0
25
50
N

Figure 18

Yearly deficits are a good indication of the condition of water resources within a watershed, andshifts in seasonality can have significant impacts on the yearly deficits. Impacts are prevalent when summer precipitation is decreasing, which many of the IPCC predictions show for the region. Figure 19indicates the yearly deficits for the basin under current conditions, and suggests that the deficits are small throughout the basin. Maps depicting yearly deficits for each scenario are available for reference in the Appendix B. The deficits in the basin increase in the northern portion (Figure20) from the baseline to the mean case scenario. Watersheds to the south do not see increases in this scenario, with the exception of watersheds 99 and 100 in New Hanover County. Change in yearly deficits from the baseline to the worst case scenario (Figure 21) is substantial in many of the Northern watersheds.

Runoff output from the mean and worst case scenarios indicates substantial decreases in available water in the southern watersheds. The best case scenario, which incorporates IPCC predictions with the greatest increase in precipitation, generates increased values for runoff. The yearly deficits show a different pattern. The baseline indicates low values for yearly deficits across the basin. However, the output from the mean and worst case scenarios indicate a substantial increase in deficit values for Northern watersheds.

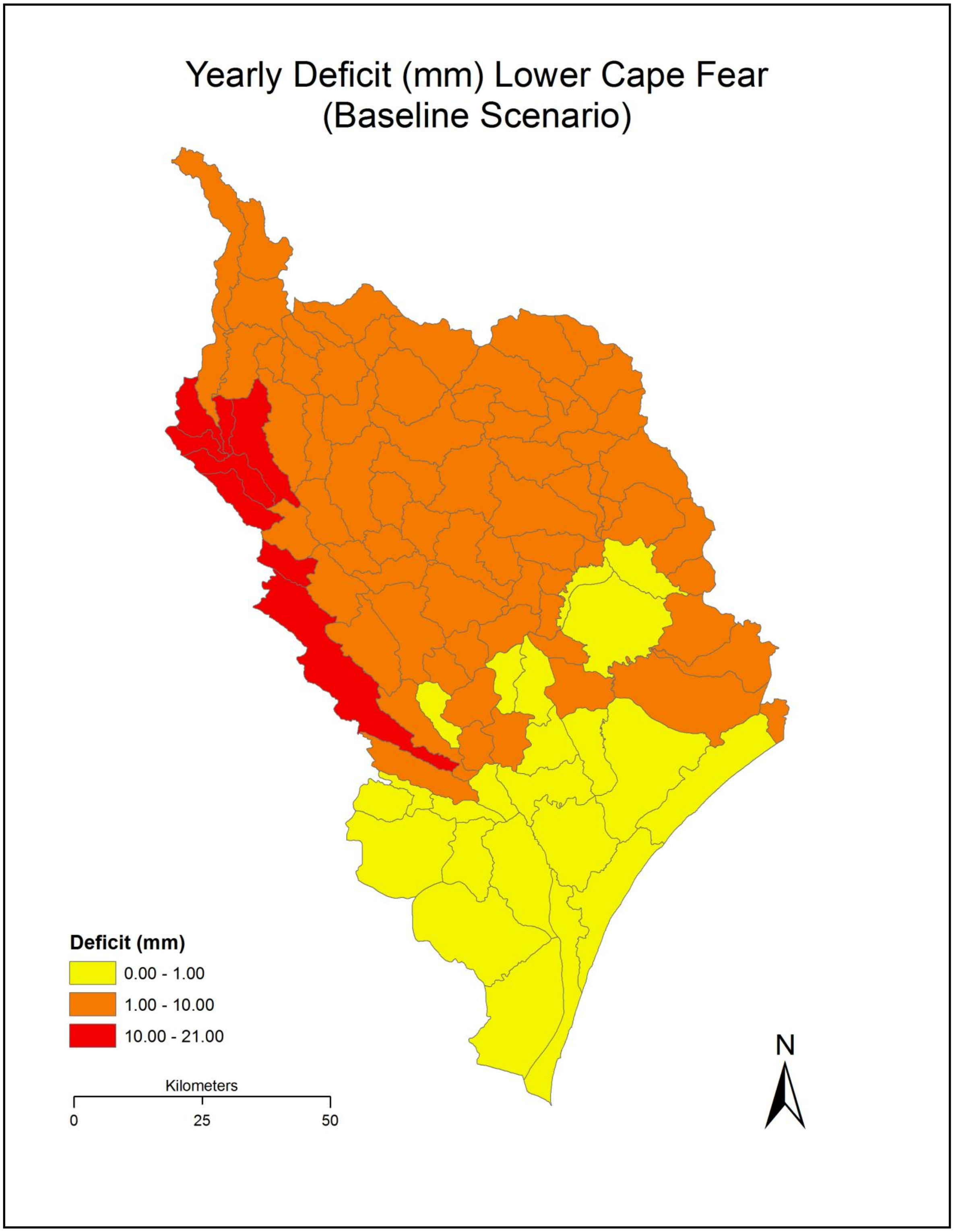
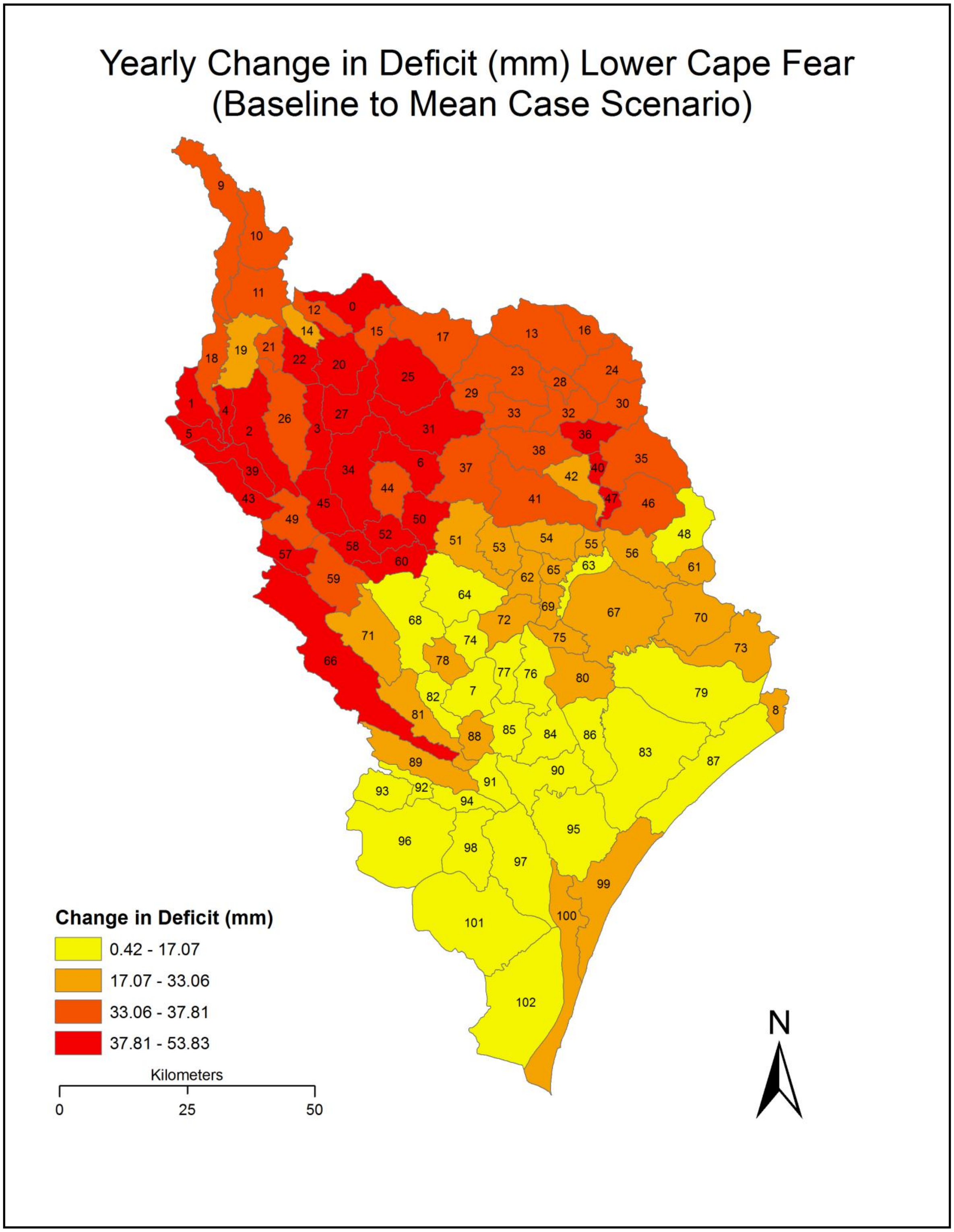

Yearly Deficit (mm) Lower Cape Fear
(Baseline Scenario)
Deficit (mm)
0.00 - 1.00
1.00 - 10.00
10.00 - 21.00
Kilometers
0
25
50
N

Figure 19


Yearly Change in Deficit (mm) Lower Cape Fear
(Baseline to Mean Case Scenario)
9
10
11
0
12
14
15
17
13
16
19
21
18
22
20
25
23
28
24
29
1
4
2
26
3
27
31
33
32
30
5
36
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76
80
66
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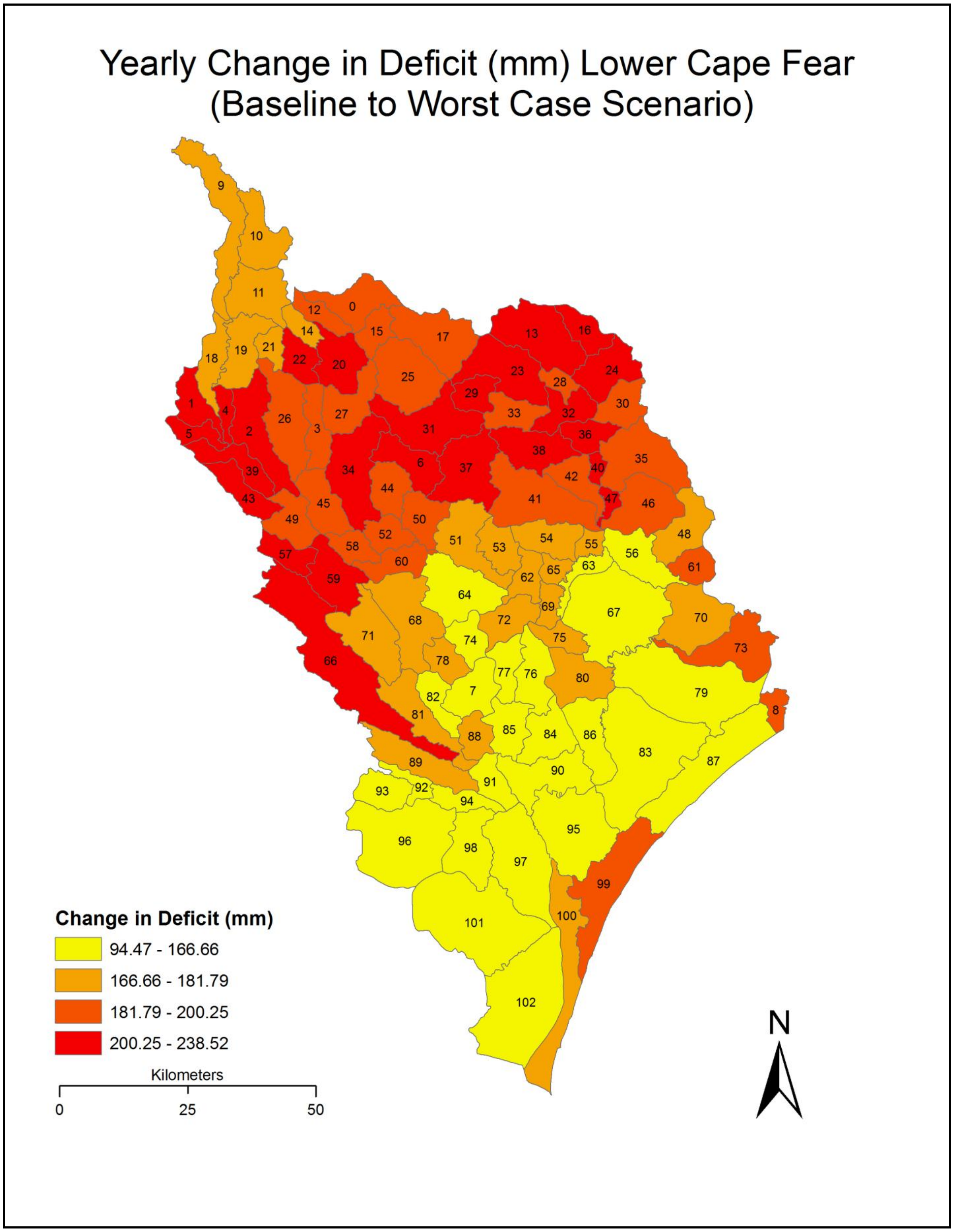
79
81
8
88
85
84
86
83
89
90
87
91
93
92
94
95
96
98
97
99
100
101
102
Change in Deficit (mm)
🟨 0.42 - 17.07
🟧 17.07 - 33.06
🟧 33.06 - 37.81
🟥 37.81 - 53.83
Kilometers
0
25
50
N

Figure 20


Yearly Change in Deficit (mm) Lower Cape Fear
(Baseline to Worst Case Scenario)
Change in Deficit (mm)
94.47 - 166.66
166.66 - 181.79
181.79 - 200.25
200.25 - 238.52
Kilometers
0
25
50
N
9
10
11
12
0
14
15
17
13
16
19
21
18
22
20
25
23
28
24
1
4
29
30
26
27
33
32
2
3
31
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6
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40
42
44
41
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7
79
81
8
88
85
84
86
83
87
89
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97
99
100
101
102

Figure 21

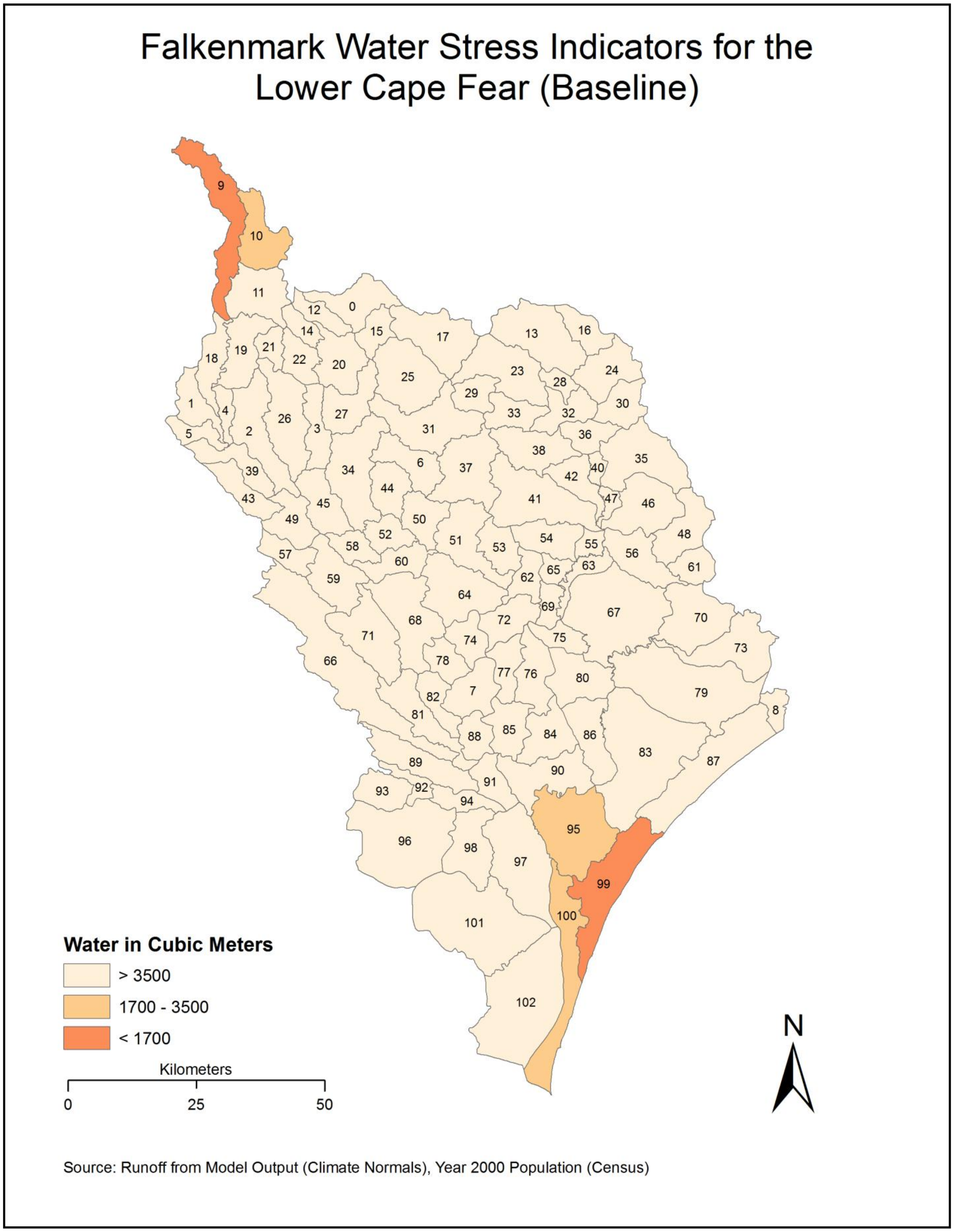
Falkenmark Indicators Results

Maps depicting water stress were generated for each of the primary scenarios under current population conditions as well as estimated 2030 population. Figure 22illustrates water stress in the basin under normal climate conditions and the current population. As the map depicts, the majority of the basin is water rich (i.e. > 3500 m^3). Two watersheds are considered water stressed (i.e. <1700 m^3). The southern watershed which is water stressed is watershed 99 and is located in New Hanover County. The watershed to the North that is water stressed is watershed 9 and is located in Harnett County. Both of these watersheds are surrounded by watersheds which are approaching water stress (i.e. 1700 - 3500 m^3).

The best case climate scenario is displayed in Figure 23. This scenario incorporates the IPCC climate prediction with the smallest increase in temperature and the greatest increase in precipitation. As the map indicates, the whole basin is free of water stress with only two areas approaching water stress. These areas correspond to the regions that showed water stress in the baseline scenario.

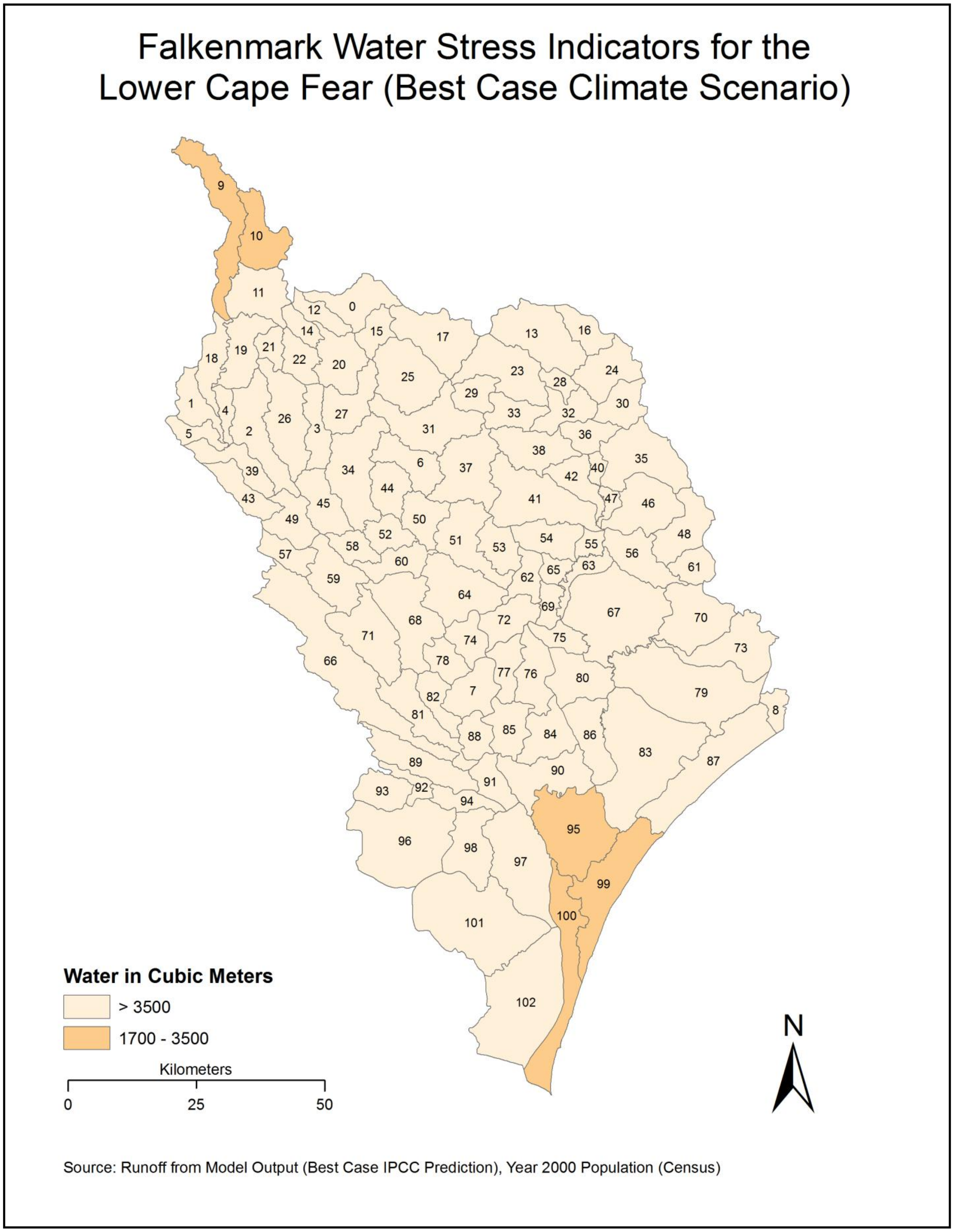
The next scenario incorporates the mean climate prediction. The same areas are highlighted in this scenario (Figure 24), with one additional area approaching water stress, watershed 62, located in Duplin County (i.e. 1700- 3500 m^3). This scenario also yields an additional watershed in the water stress category. Watershed 95, located in New Hanover County becomes water stressed under conditions consistent with mean IPCC climate predictions. The worst case climate prediction intensifies the stress that is present in the baseline (Figure 25). The watersheds that were approaching water stress are now water stressed and the two that were water stressed are now water scarce (i.e. < 1000 m^3) . In addition to the main stress regions in the north and south, four other watersheds are approaching water stress.

These maps depict the climate change scenarios with the current population. However, the population within the basin has grown rapidly and is projected to continue to grow. Therefore, the same analysis was conducted using predicted population.


Falkenmark Water Stress Indicators for the Lower Cape Fear (Baseline)

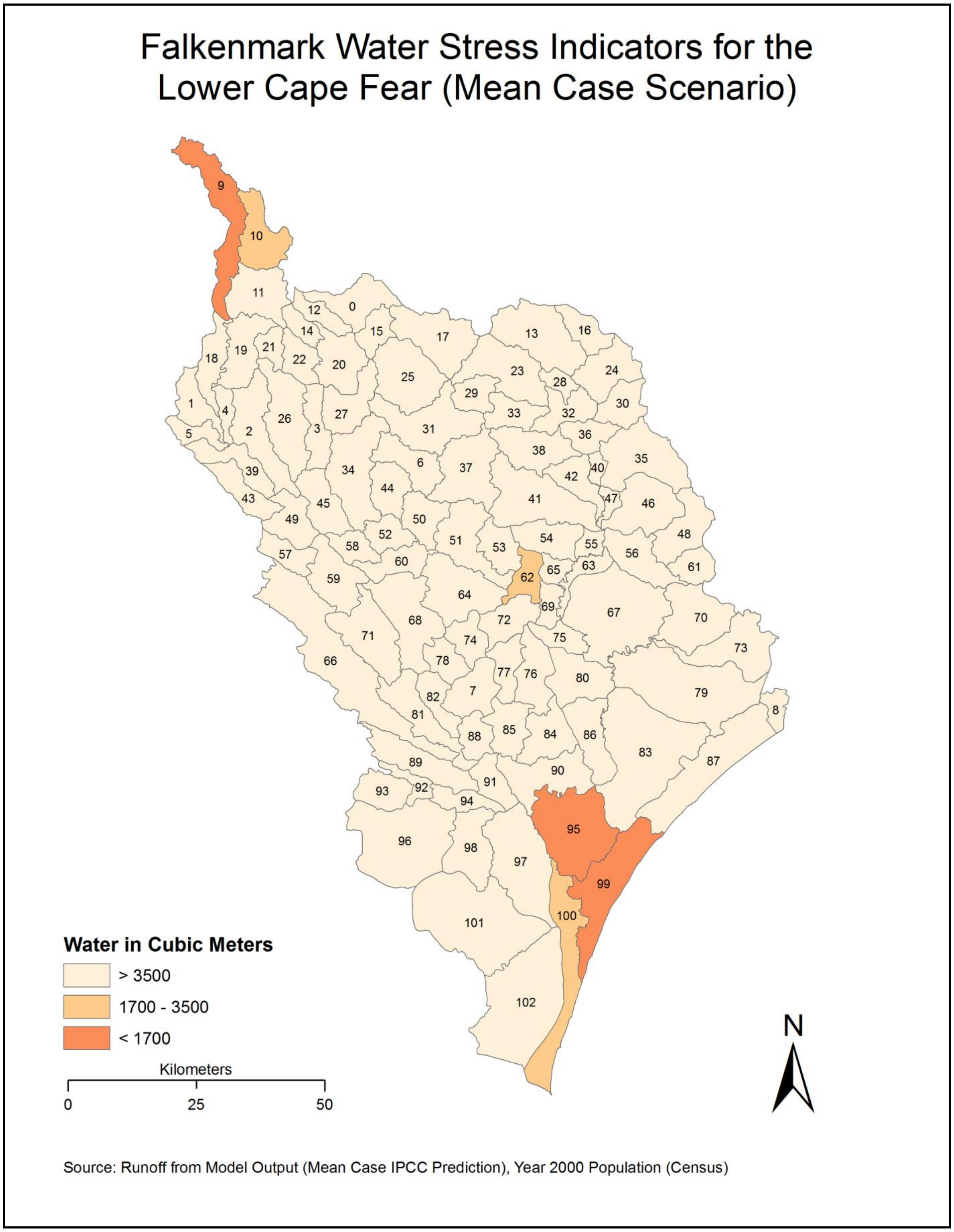
Source: Runoff from Model Output (Climate Normals), Year 2000 Population (Census)

Figure 22


Falkenmark Water Stress Indicators for the Lower Cape Fear (Best Case Climate Scenario)

Source: Runoff from Model Output (Best Case IPCC Prediction), Year 2000 Population (Census)

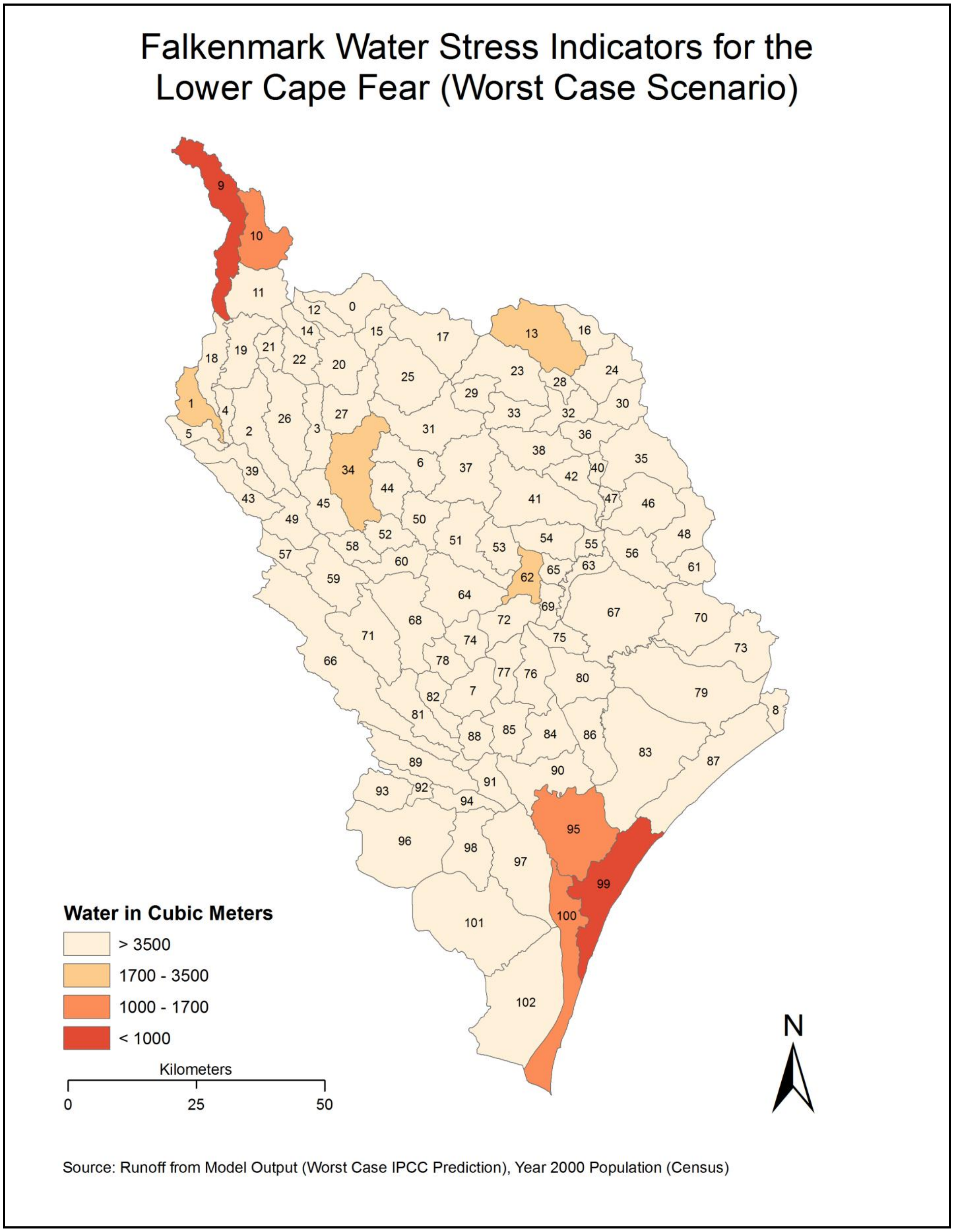
Figure 23



Falkenmark Water Stress Indicators for the Lower Cape Fear (Mean Case Scenario)

Source: Runoff from Model Output (Mean Case IPCC Prediction), Year 2000 Population (Census)

Figure 24

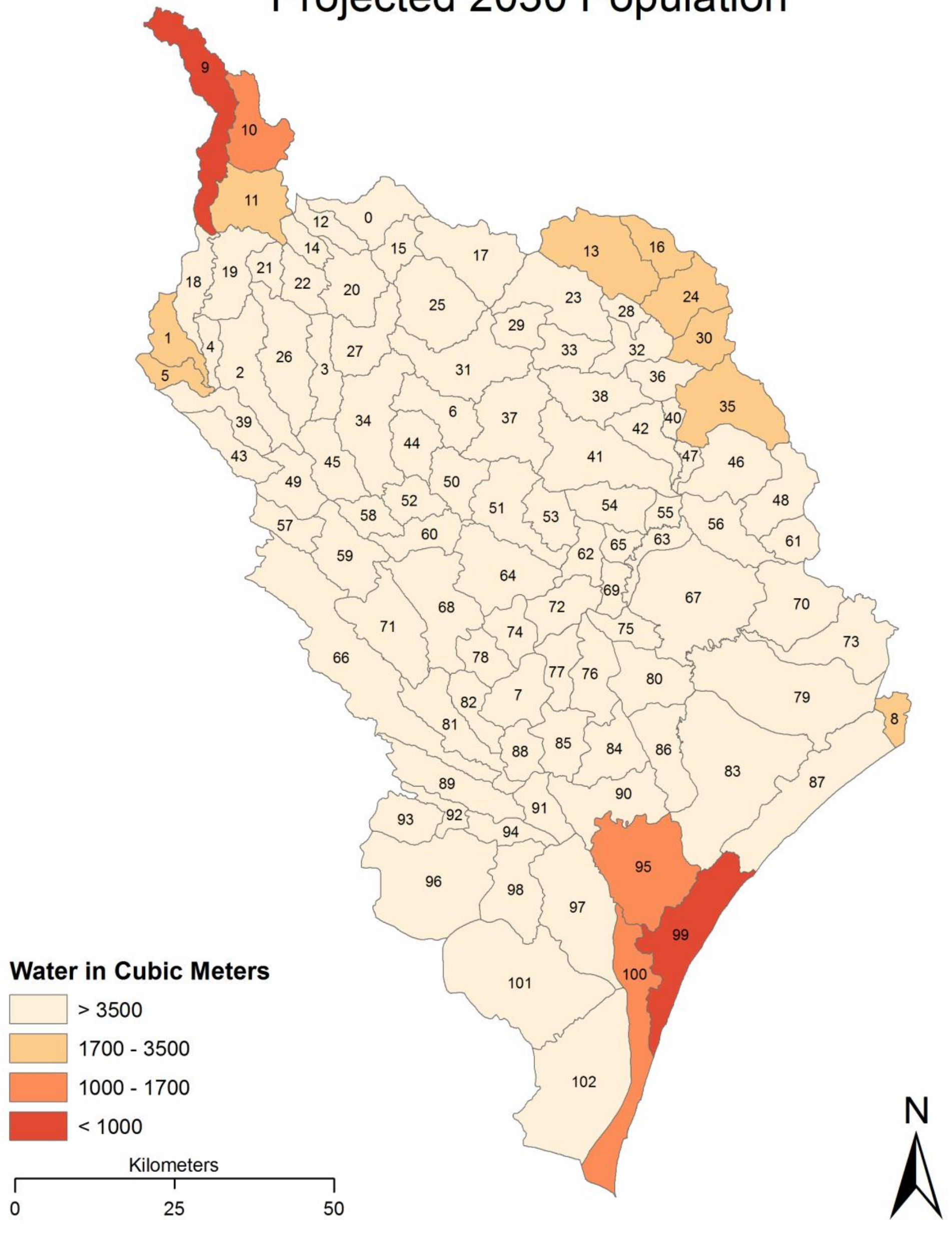


Source: Runoff from Model Output (Worst Case IPCC Prediction), Year 2000 Population (Census)

Figure 25

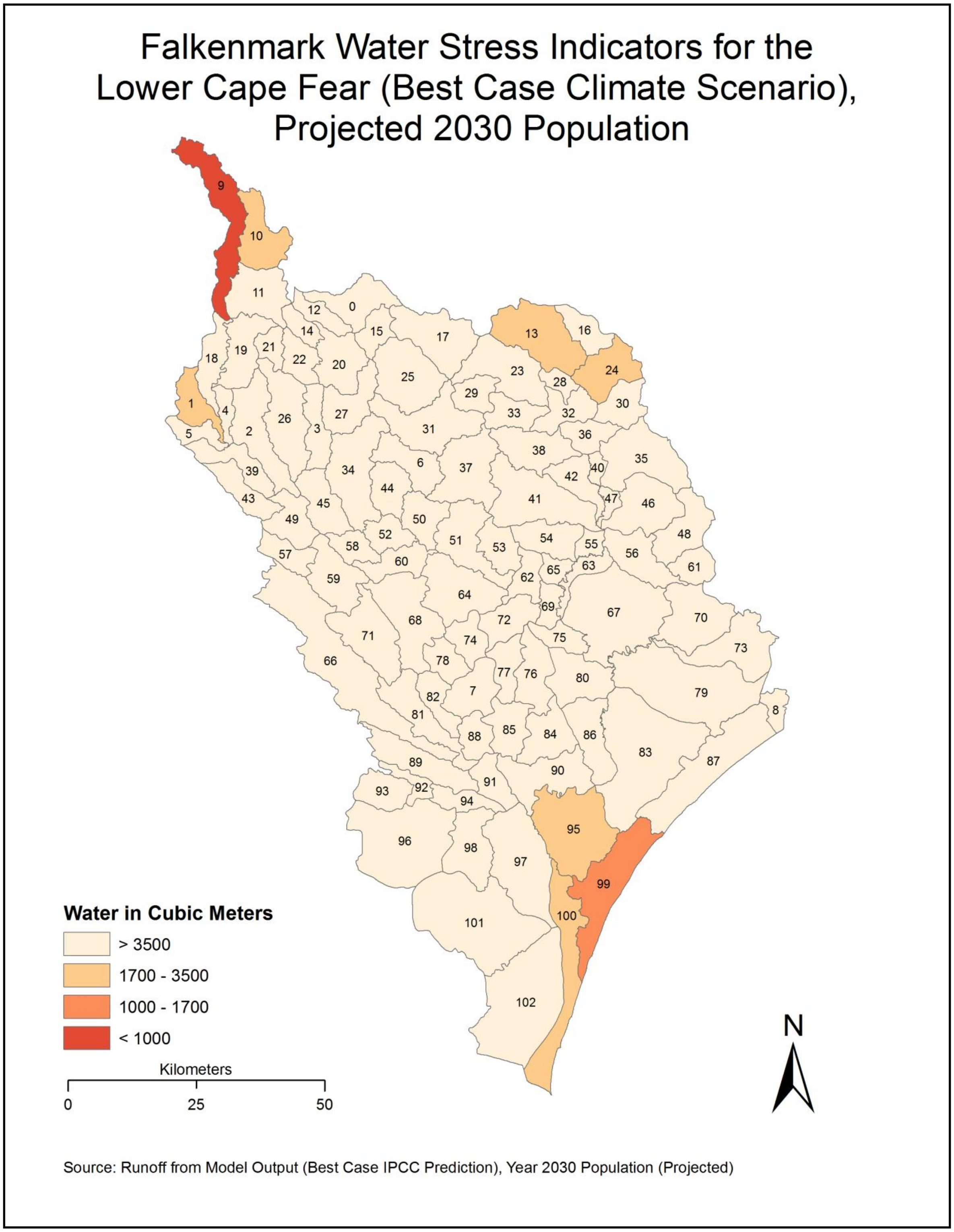
A baseline was also established for the population projection analysis. The first step was to analyze water stress in the basin with the climate normals and 2030 projected population. The water stress for this scenario is displayed in Figure 26. As the map depicts, stressed areas correspond to the same areas that were highlighted in the baseline for the current population (Figure 22). However, the watersheds that were water stressed in Figure 22 are now water scarce,and the watersheds that were approaching water stress in Figure 22 are now water stressed. A cluster of watersheds in Duplin and Wayne Countiesis approaching water stress in this scenario, which did not show up in the scenario with the current population. In the best case climate scenario (Figure 27), watershed 9 in Harnett County is water scarce, while watershed 99 in New Hanover County is water stressed. There is still a cluster of concern in Duplin and Wayne Counties under this scenario. Output from the mean climate prediction mirrors that of the baseline (Figure 28) with some additional watersheds approaching water stress. Output from the final scenario, which incorporates the worst case climate prediction, increases the number of watershedsshowing water stress (Figure 29).In addition, the cluster of watersheds in Duplin and Wayne Counties which were transitioning to water stress in earlier scenarios is now water stressed. Further, the number of watersheds showing water scarcity increases and watershed number 9 which had the most stress in the other scenarios is now in a category defined as absolute scarcity (i.e. $< 500\ m^3$). All of New Hanover County is defined as water scarce in this scenario.

Falkenmark Water Stress Indicators for the Lower Cape Fear (Climate Normals), Projected 2030 Population



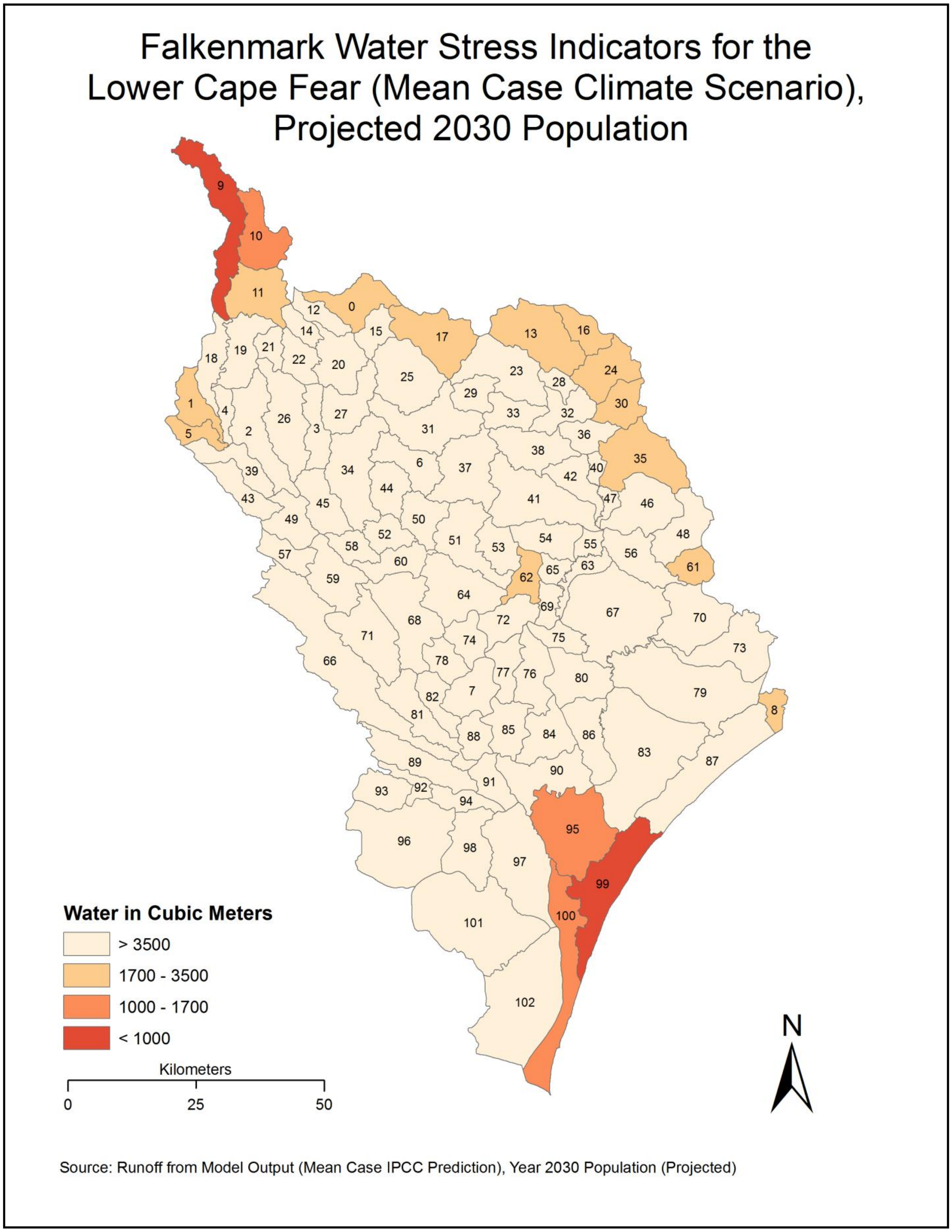
Source: Runoff from Model Output (Climate Normals), Year 2030 Population (Projected)

Figure 26



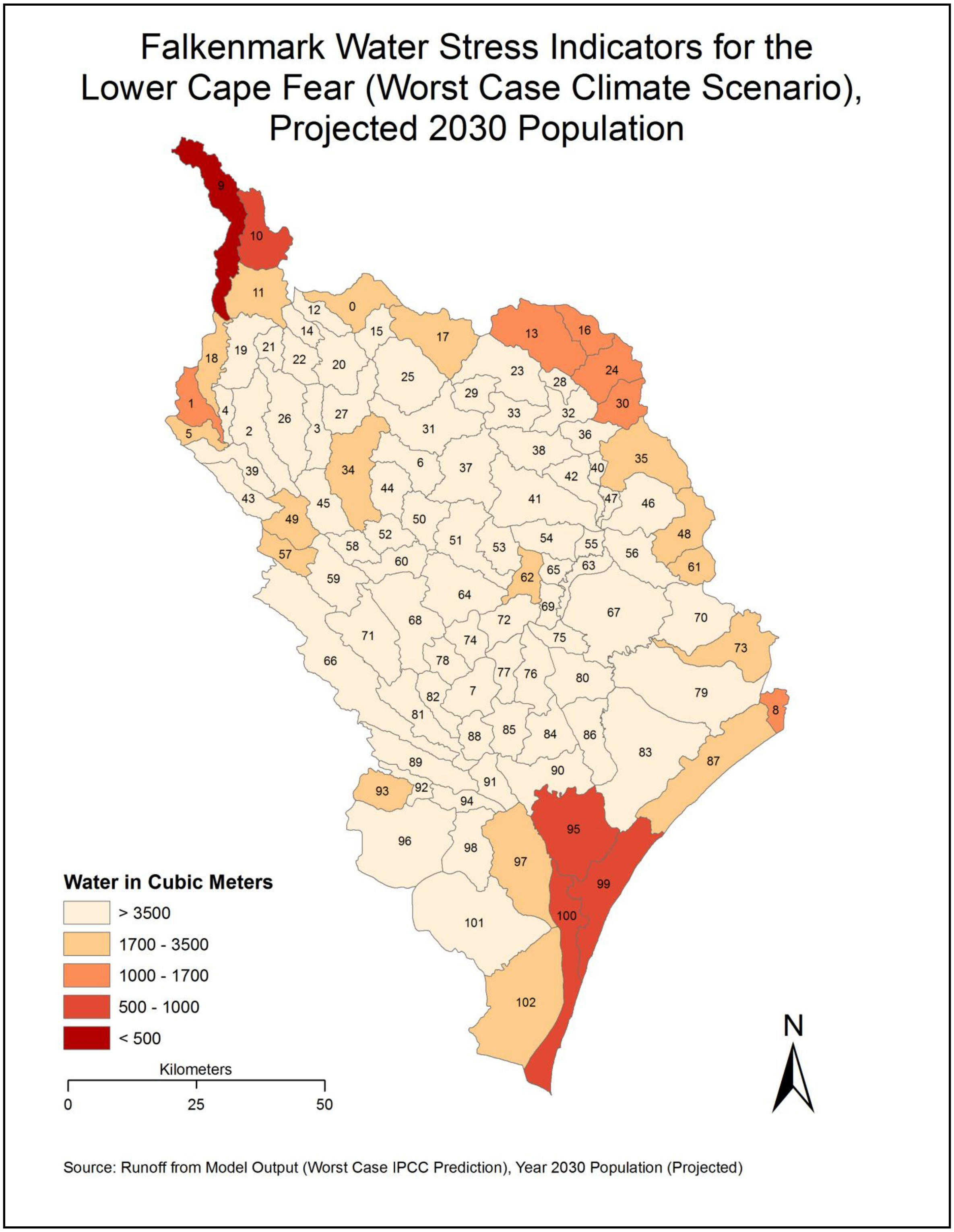
Source: Runoff from Model Output (Best Case IPCC Prediction), Year 2030 Population (Projected)

Figure 27



Source: Runoff from Model Output (Mean Case IPCC Prediction), Year 2030 Population (Projected)

Figure 28

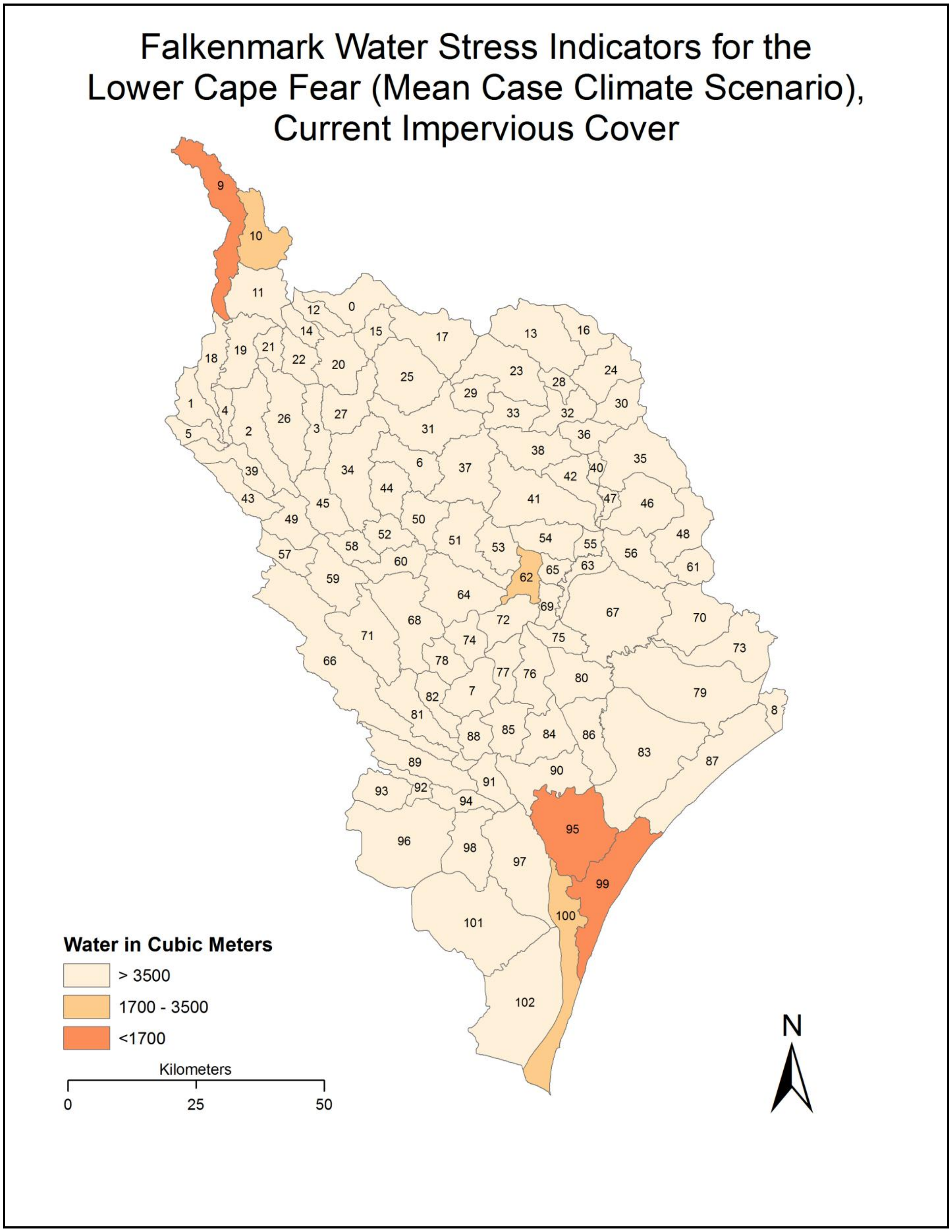


Source: Runoff from Model Output (Worst Case IPCC Prediction), Year 2030 Population (Projected)

Figure 29

As a result of the Falkenmark water stress analysis, two regions are identified as primary concern areas. These areas consist of New Hanover County and eastern Harnett County. Another area which could produce problems and shows up in the worst case climate prediction is located in northeast Duplin County and Wayne County (Figure 29). While the majority of the basin is water rich and the outlook under various climate predictions looks good, there are areas of concern. With the possibility of decreasing availability due to climate change coupled with increased demand as populations grow in these regions, issues could arise in the future.

Thus far, the scenarios discussed have been estimated using extrapolated impervious surface cover. Model runs which incorporated the current impervious cover in the basin vary little from that of the extrapolated impervious cover, in part because throughout most of the basin, the impervious cover is not growing much if at all. Figure 30 illustrates the Falkenmark water stress indicators, based on the mean IPCC climate, current population, and current impervious cover. This illustration is an exact match of Figure 24, which utilizes the extrapolated impervious cover. Analysis using the current impervious cover vs. extrapolated impervious cover indicates that impervious surface cover may have minimal impacts on future water resources in this region, while climate and population growth are the main determining factors. However, areas within the basin which are densely populated could produce conflicting results if the same analysis is conducted on finer scale watersheds. Delineating fine scale watersheds can better capture areas with high impervious cover and could be the focus of future research.


Falkenmark Water Stress Indicators for the
Lower Cape Fear (Mean Case Climate Scenario),
Current Impervious Cover
9
10
11
12
0
14
15
17
13
16
18
19
21
22
20
25
23
24
28
29
1
4
26
27
33
32
30
5
2
3
31
36
38
35
39
34
6
37
40
42
43
44
41
47
46
45
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73
66
78
77
76
80
79
82
7
81
8
88
85
84
86
83
89
90
87
91
93
92
94
95
96
98
97
99
100
101
102
Water in Cubic Meters
> 3500
1700 - 3500
<1700
Kilometers
0
25
50
N

Figure 30

CHAPTER 6: DISCUSSION AND CONCLUSIONS

Discussion

Numerous variables essential to assessing water resources were examined in depth in this analysis. The output from the model allowed detailed study of the impact of future impervious cover and climate change scenarios on yearly runoff, yearly deficits, and coupled with the Falkenmark water stress indicators, accounted for the impact of population growth. Each of these metrics plays a role in assessing the state of water resources in the future. Runoff values are essentially the available surface water within each watershed, so yearly deficits are a good indication of drought conditions. The Falkenmark water stress indicators are perhaps the best metric for assessing water resources as they incorporate available water (runoff) and population demand. Runoff is an important variable, but population values are needed in order to assess whether the runoff is sufficient to sustain the population. The combination of these variables provides insight into the state of the basin in the future.

The current state of runoff is variable throughout the basin. Watersheds in the Northern portion of the basin indicate lower values for available water. However compared to the population in those areas (Figure 2), the amount of available water is sufficient to sustain the people residing within the watersheds. Southern watersheds, especially those in New Hanover County, are densely populated, but the runoff values are higher and thusbetter accommodate the increased demand. While water availability appears to be sufficient across the basin in relation to the population with the baseline scenario, the mean and worst case predictions show substantial decreases in runoff in central southern watersheds. This could present significant problems due to the dense population in this region.

Deficits in the basin do not appear to pose a problem in most of the southern basin, with elevated values in the northern watersheds. Shifts in yearly deficits could be an indication of gradual changes in the climate conditions for the basin. Currently, the basin is classified as Cfain the Koppen climate classification scheme. Cfa climates are defined as humid subtropical. Yearly deficit is a useful variable to examine possible transitions to other climate types. While deficit is highly dependent on temperature and precipitation, impervious cover factors in as well. The baseline yearly deficits show low values across the basin, indicative of a climate such as Cfa. However, when looking at the change from the baseline to the mean prediction, many of the northern watersheds are increasing at a rapid pace. This is primarily due to climate change as the impervious cover in these areas has remained fairly constant in both the historical record and extrapolated predictions. However, watersheds 99 and 100, located in New Hanover County where the climate is similar to the surrounding watersheds, indicate a greater increase in yearly deficits than the surrounding watersheds. This is related to the impervious cover in these watersheds, which has increased at a more rapid pace than any other region in the basin. The worst case scenario increases the deficits over 90 mm throughout the basin. The majority of the northern watersheds show substantial increases, around 200 mm. The impact of impervious cover is visible here as well, as watersheds 99 and 100 still show a greater change than the surrounding watersheds.

Most indicative of the state of future water resources in the region is the Falkenmark water stress indicators for each scenario. While most of the basin is water rich under current conditions, two watersheds show water stress, one of which is in New Hanover County and the other in Harnett County. As the runoff analysis indicated, available water decreases in most of the southern watersheds. This will be detrimental to these watersheds as they have elevated populations. Water stress is calculated by taking into account available water (runoff) and watershed population. The elevated population and decreasing runoff in New Hanover County watersheds transition the County from minimal water stress to primarily water stressed, with the possibility of water scarcity, assuming current population. Watershed 9 in Harnett County is also problematic. This watershed is stressed in the baseline scenario and could transition to water scarce if the worst case IPCC scenario is realized. After incorporating the 2030 population predictions, the outlook for New Hanover and Harnett further degrades and concerns for Duplin and Wayne Counties arise as areas which could potentially see water stress in the future. The potential future stress in Wayne and Duplin Counties is most likely linked to the proximity of the watersheds to Seymour Johnson Air Force base and the growth associated with it.Analysis of the water stress indicators in the basin indicates two distinct problem areas. One is in the Southern basin centered on New Hanover County, and also the largest city, in Wilmington. The other is in Northern region around Harnett County.

Analysis to determine the impacts of impervious cover in the basin did not yield any significant results. Model runs under varying climate scenarios, utilizing both extrapolated impervious cover and current values, produced similar results for runoff and Falkenmark water stress indicators, as comparison of Figures 24 and 30 indicates. However, in New Hanover County watersheds, which show substantial increases in impervious cover, significant changes in yearly deficits from the current impervious cover to 2100 impervious cover are seen.

Limitations to the Research

This analysis provides a detailed look at the range of possibilities for water resources in the Lower Cape Fear River basin. However, there are certain limitations to the research. The first relates to the soil moisture capacity parameter which needs to be established for each watershed in the water balance model. In order to determine soil moisture capacity, a global dataset was utilized. This is the best available data without actually going to collect field measurements in each watershed, but it is not sufficiently detailed. In the future if funding and time are available, the model should be revisited with values retrieved from actual field measurements.

The next limitation is that of the climate change scenarios. Regional climate change scenarios are not accepted as being very reliable. Therefore, various IPCC scenarios were incorporated in order to provide a range of possible future water resource conditions within the basin. Even these scenarios have numerous uncertainties, especially when downscaled and applied to the southeastern United States (State Climate Office of North Carolina 2011). As our knowledge of climate change becomes more certain, scenarios can be repeated.The third limitation is the fact that water is not routed through the basin in this research, so the influence of upstream watersheds is not directly incorporated. The purpose of this research was to examine the natural runoff on a local scale and therefore water routed through the basin was not a focus of this research. In addition, in only the best case scenarios was there an increase in runoff, with the downstream watersheds increasing the least.

While there are some limitations, the results provide a range of possibilities for the future. This information is essential to planners and government officials in order to sustain future populations. In addition to providing a window into the possibilities of the future, another result of this research is a framework for future research. Since the model is established, it can be revisited as new climate projections and soil moisture data become available.

Conclusion

During the course of this project, a methodology has been developed which can be customized to fit the needs of countless basins in order to assess future water resource conditions. In addition to the outline of the methodological approach is a detailed analysis of current and future conditions in the Lower Cape Fear River Basin, located in Southeast North Carolina. As a result of this analysis, a number of areas have been identified as problematic in their ability to sustain future populations.

Regions highlighted in Figure 31 represent areas experiencing water stress or areas that will experience water stress in the future. The values depicted in this map are for the mean IPCC prediction and the 2030 population, as the mean prediction is the best guess for future climate conditions. Also, the 2030 population is reasonable as population growth in this region shows no signs of coming to a halt.This knowledge provides planners with valuable information which could lead to the implementation of policy and infrastructure toalleviate anticipated stress in the future. Results indicate that the region, which has historically been water rich, is transitioning to one facing potentially major water resource issues. The primary culprits for this shift are climate change and the potential for future climate change as well as the ballooning population, which shows no signs of letting up. Even when removing the population factor and just looking at the available water (runoff) within each watershed, the future looks bleak, as runoff values are decreasing across the basin in each scenario except for that of the best case climate prediction.

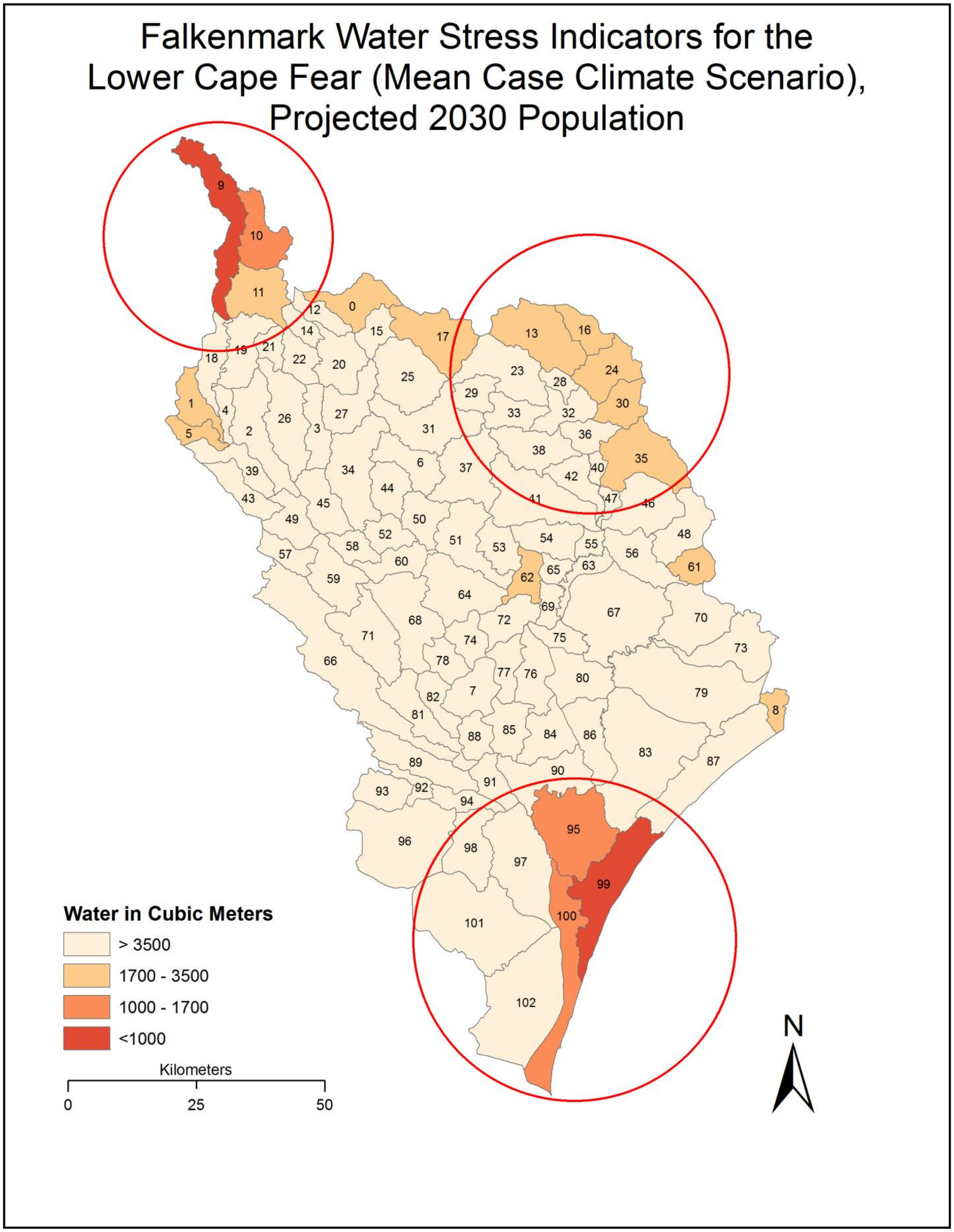


Figure 31 – Regions in danger of water stress (areas contained within red)

However, while the runoff in many of the watersheds is decreasing dramatically, the majority of these watersheds are still considered water rich as population demand does not exceed the available water. Yearly deficits in the basin are also telling. Yearly deficits reflect the difference between Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET). The deficits in the basin increase in the mean and worst case scenarios, as yearly deficits are highly dependent on seasonality. The fall and winter are usually periods of recharge as the temperature is decreasing, which in turn decreases evapotranspiration. The opposite is true for the spring and summer when temperatures are high. Temperature is the main determining factor in this region as the precipitation is distributed fairly evenly throughout the year. However, with the mean and worst case climate predictions, precipitation decreases in summer months while the temperature is increasing, therefore causing the yearly deficits to increase. This could play a role in increasing the frequency of drought conditions within the basin.

Whilegrowth in impervious cover was expected to have a significant impact on the results of this research, the rate of growth throughout the basin was not significant. In areas such as New Hanover County, where the impervious growth was substantial, increases in yearly deficits were present, while runoff and water stress remained fairly constant. As such, in the Lower Cape Fear River basin, the main determining factors contributing to the future water resource health of the basin are climate and population. As Figures 22 – 25 indicate, climate has a substantial impact. The negative impacts of climate change are compounded by the effects of a rapidly growing population, as Figures 27-29 indicate.

This research has answered the original questions that were addressed. The influence of climate change is apparent in the results and could produce significant problems in the future. The role of impervious cover was found to be insignificant in this basin, although this may not be the case in many other regions.With respect to metrics for estimating the combined influence of environmental change, population growth, and climate change, the Falkenmark water stress indicators are a proven means of tying availability to population, and were effectively implemented in this research.

Table 6 is a summary table illustrating the impact of population growth, climate change, and impervious surfaces in six watersheds that are identified as problem areas. Watersheds 9, 10, and 11 are in and around Harnett County. Watersheds 95, 99, and 100 are in New Hanover County. The runoff values drop by as much as 97 mm from scenario 1 (climate normals, 2100 IS cover) to scenario 3 (mean climate prediction, 2100 IS Cover). Scenario nine is also run with the mean climate prediction but incorporates current impervious cover conditions as opposed to the projected 2100 IS cover. There is little variance between these two scenarios. The summary of the Falkenmark indicators, which tie water availability to the population size, indicates that population has a more profound impact on water resources than climate change. Scenarios 1 and 3 both incorporate the 2000 Census population while the climate changes. The values for each watershed decrease, with the largest decrease being about 654 m^3. Scenario 7 which incorporates the same climatic conditions as scenario 3 with projected 2030 Census population shows drastic decreases. For example, watershed 11 decreases over 2000 m^3. This table suggests that, while climate change will likely have an adverse impact on future water availability, this impact is exacerbated by population growth, both with and without climate change.

Table 6 – Summary – Climate Change Vs. Population Growth

Model Output Runoff (mm)			
Watershed ID	Scenario 1	Scenario 3	Scenario 9
9	363.7675	320.131495	321.202349
10	363.414598	318.743343	320.347854
11	363.180235	320.313689	319.778588
95	523.954704	426.610518	420.971669
99	523.467004	442.628232	420.630622
100	606.671822	542.477249	523.735099

Falkenmark Water Stress (m^3 Per person Per Year)			
Watershed ID	Scenario 1	Scenario 3	Scenario 7
9	1538.591702	1354.028775	584.37969
10	2417.534533	2120.368978	1143.44666
11	5543.306692	4889.024353	2885.23149
95	1978.495224	1610.915726	1134.02808
99	1519.892908	1285.176534	777.749701
100	2430.509313	2173.326597	1408.88341

The importance of this research is far reaching. Results from this analysis could be beneficial to planners throughout the region, allowing them toalleviate some of the deficits that lie ahead. Many different avenues can be explored with the methodology outlined here. For instance, if, in the future,available water will no longer be able to support the population, it may be necessary toseek water from other watersheds or as people migrate to other watersheds, scenarios can be estimated for these possibilities and potential conditions can be evaluated. These situations could well lead to conflict among counties, something that planning based on models like the one presented here can help to avoid. With this model in place, future research can take into account the possibility of shifts in population distribution. Future analysis could also incorporate finer scale watersheds to investigate if the results differ from those found here.

Also, with funding and more time, soil moisture capacity could be tested in each watershed to provide even more detail. The possibilities are many and are facilitated by the methodology that was used here.

Research of this nature is growing in importance, as issues regarding water resources are increasing every day. The threat of climate change and a ballooning population indicate potential trouble ahead. As such, the time to act is now in order to plan for future conditions. However, before planning can commence, a snapshot of what the future may look like is needed. This is where research such as this is imperative.

REFERENCES CITED

Arnell, N. W., 1999.Climate Change and Global Water Resources.*Global Environmental Change*, **9**, S31-S49.

Batjes, N. H. (ed.), 2000. Global Data Set of Derived Soil Properties, 0.5-Degree Grid (ISRIC-WISE [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. doi:10.3334/ORNLDAAC/546.

Brubaker, K. L., D, Entekhabi,P.S. Eagleson, 1993.Estimation of Continental Precipitation Recycling.*Journal of Climate*,**6**, 1077-1089.

City of Wilmington North Carolina, 2010.*Facts and Figures*. http://www.ci.wilmington.nc.us/city_manager/facts_figures.aspx.

Cooke, R.A,., S. Mostaghimi, 1992. A Microcomputer-Based Routine for Obtaining Mean Watershed Precipitation From Point Values. *Computers & Geosciences*, **18**, 823-837

D'Almeida, C., C. J. Vorosmarty, J. A. Marengo, G. C. Hurtt, L. S. Dingman, and B. D. Keim, 2006. A Water Balance Modelto Study the Hydrological Response to Different Scenarios of Deforestation in Amazonia.*Journal of Hydrology*, **331**, 125-136.

Dingman, L.S., 2008. *Physical Hydrology*, Second Edition. Waveland Press, INC.Long Grove, IL

Falkenmark, M., J. Lundqvist, and C. Widstrand, 1989. Macro-Scale Water Scarcity Requires Micro-Scale Approaches. *Natural Resources Forum*, , 258-267.

Hamon, W.R., 1961.Estimating pPotentialEvapotranspiration.*Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers*, **87**, 107–120.

Huntington, T. G., 2005. Evidence for Intensification of the Global Water Cycle: Review and Synthesis. *Journal of Hydrology*, **319**, 83-95.

Hurd, B., N. Leary, R. Jones, and J. Smith, 1999.Relative Regional Vulnerability of Water Resources to Climate Change.*Journal of the American Water Resources Association,* **35**, 1399-1409.

Intergovernmental Panel on Climate Change(IPCC), 2007.*IPCC Fourth Assessment Report*., http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Kutzbach, J. E., J. W. Williams, and S. J. Vavrus, 2005.Simulated 21st Century Changes in Regional Water Balance of the Great Lakes Region and Links to Changes in Global Temperature and PolewardMoisture Transport.*Geopyhsical Research Letters,* **32**, 1-5.

Milly, P. C., K. A. Dunne, and A. V. Vecchia, 2005.Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate.*Nature*, **438**, 347-350.

Mulholland, P. J. G.R. Best, C.C. Coutant, G.M., Hornberger, J.L. Meyer, P.J. Robinson, J.R. Stenberg, R.E. Turner, F. Vera-Herrera, R.G. Wetzel, 1997.Effects of Climate Change on Freshwater Ecosystems of the South-Eastern United States and the Gulf Coast of Mexico. *Hydrological Processes,* **11**, 949-970.

National Oceanic and Atmospheric Administration, 2010, Coastal Services Center,*C-CAP Regional Land Cover*. http://www.csc.noaa.gov/digitalcoast/data/ccapregional/index.

North Carolina Department of Environment and Natural Resources (NCDENR), 2011.Division of Water Resources, *Water Withdrawals*,http://www.ncwater.org/Water_Withdrawals/ResultsTabJS.php?tab=map.

Oak Ridge National Laboratory,n.d.*U.S. Historical Climatology Network*. http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn_map_interface.

Postel, S. L., 2000.Entering an Era of Water Scarcity: The Challenges Ahead.*Ecological Applications,* **10**, 941-948.

Praskievicz, S., and H. Chang, 2009.A Review of Hydrological Modelling of Basin-Scale Climate Change and Urban Development Impacts.*Progress in Physical Geography,* **33**, 650-671.

Rijsberman, F. R., 2006. Water Scarcity: Fact or Fiction? *Agricultural Water Management,* **80**, 5-22.

Robinson, P. J., 2006.Implications of Long-Term Precipitation Amount Changes for Water Sustainability in North Carolina.*Physical Geography,* **27**, 286-296.

Roy, S. B., P. F. Ricci, K. V. Summers, C. Chung, and R. A. Goldstein, 2005.Evaluation of the Sustainability of Water Withdrawals in the United States, 1995 TO 2025. *Journal of the American Water Resources Association,* **41**, 1091-1108.

Shen, S.S.P., P. Dzikowski, G. Li, and D. Griffith, 2001. Interpolation of 1961-1997 Daily Temperature and Precipitation Data onto Alberta Polygons of Ecodistrict and Soil Landscapes of Canada .*American Meteorological Society,* **40**, *2162-2176*

State Climate Office of North Carolina, 2010.*Climate Division Data*.NC State University.http://www.nc-climate.ncsu.edu/climate/climdiv.php.

State Climate Office of North Carolina, 2011.*Climate Change in North Carolina*.NC State University.http://www.nc-climate.ncsu.edu/climate/climate_change

Sun, G., S. G. McNulty, J. A. Moore Myers, and E. Cohen, 2008.Impacts of Multiple Stresses on Water Demand and Supply across the Southeastern United States.*Journal of the American Water Resources Association,* **44**, 1441-1457.

Thornthwaite, C.W., 1948, An Approach Toward a Rational Classification of Climate.*Geographical Review*, **38**, 55–94.

Trenberth, K. E., 1999.Conceptual Framework for Changes of Extremes of the Hydrological Cycle with Climate Change.*Climatic Change,* **42**, 327-339.

Tsakiris, G., D. Pangalou, and H. Vangelis, 2007.Regional Drought Assessment Based on the Reconnaissance Drought Index (RDI).*Water Resources Management,* **21**, 821-833

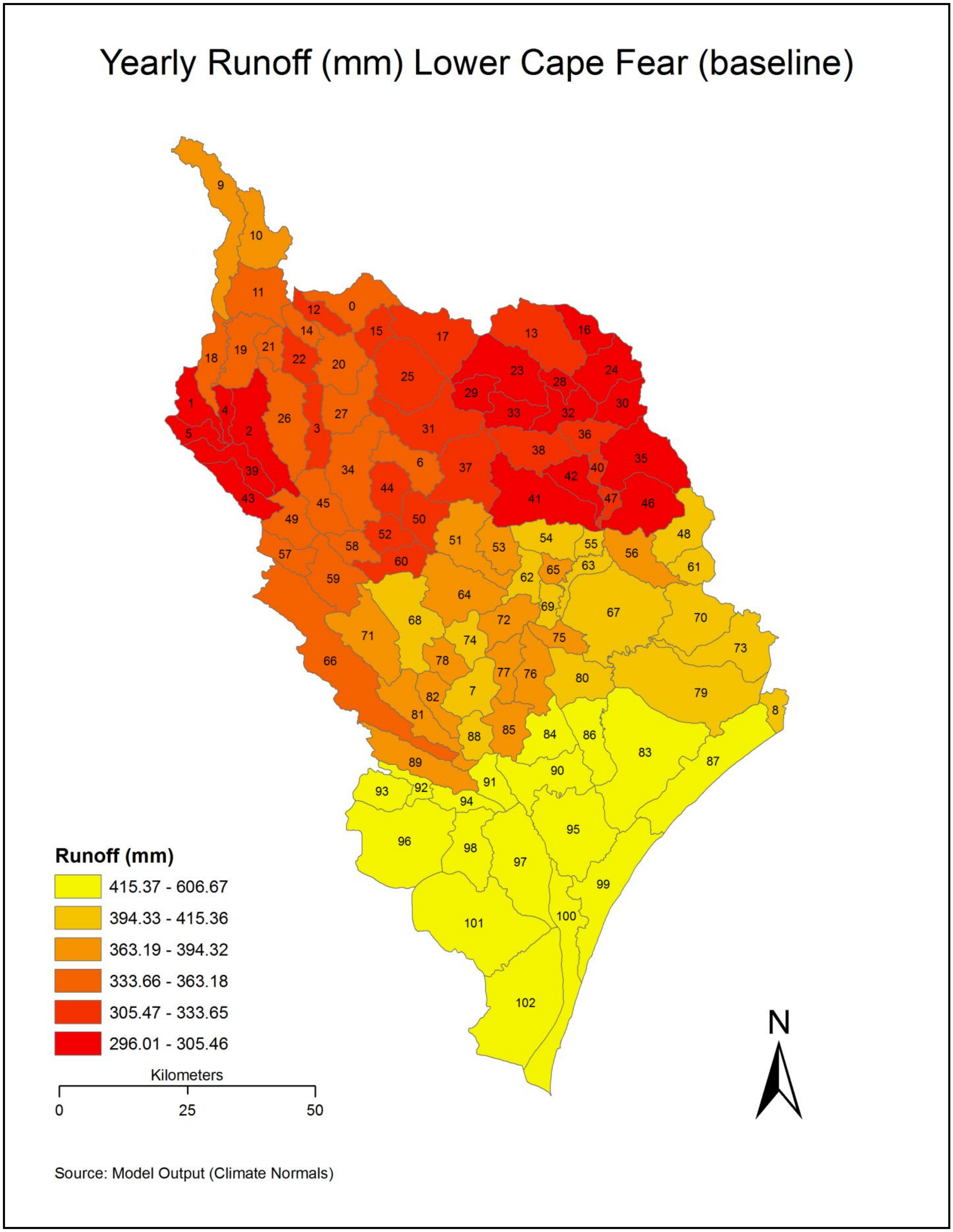
United States Census Bureau, 2011.*Data Access Tools*.http://www.census.gov/main/www/access.html.

United States Geological Survey, 2010.Thornthwaite Monthly Water Balance Model.*Watershed Modeling*. http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/software/thorn_s/thorn.shtml.

Vicuna, S., and J. A. Dracup, 2007.The Evolution of Climate Change Impact Studies on Hydrology and Water Resources in California.*Climatic Change,* **82**, 327-350.

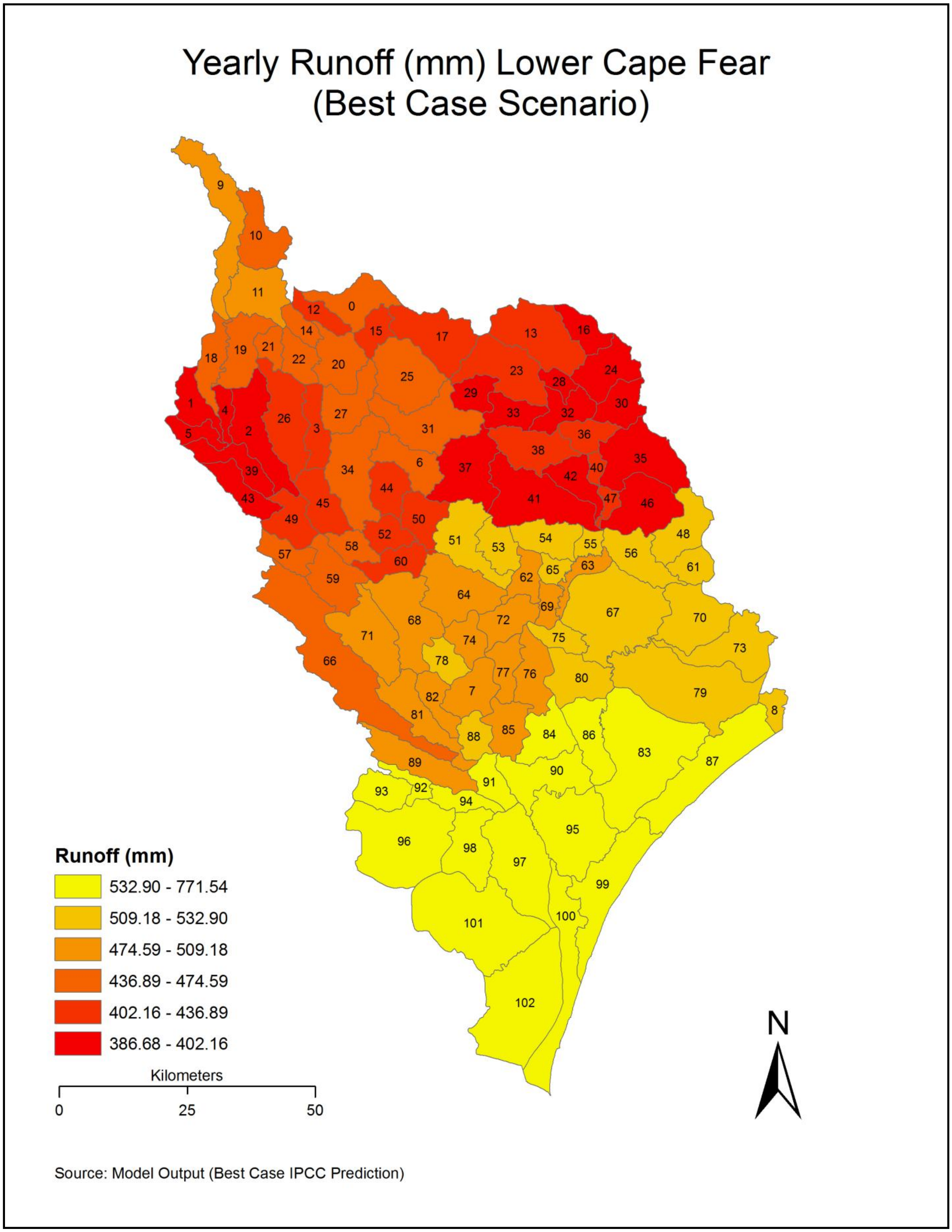
Xu, C. Y., and V. P. Singh, 1998.A Review on Monthly Water Balance Models for Water Resources Investigations.*Water Resources Management*, **12**, 31-50.

APPENDIX A: MODEL OUTPUT FOR RUNOFF

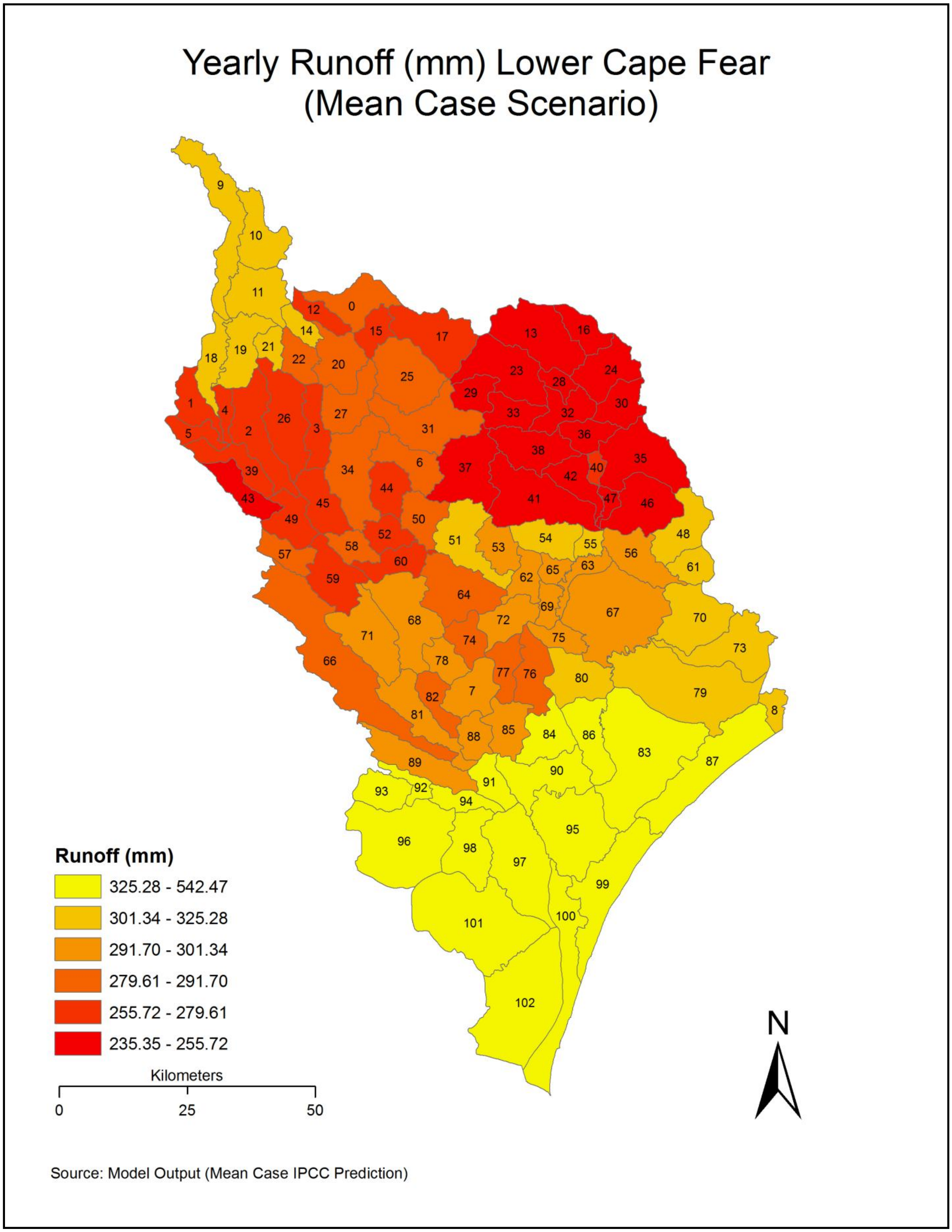


Yearly Runoff (mm) Lower Cape Fear (baseline)

Source: Model Output (Climate Normals)


Yearly Runoff (mm) Lower Cape Fear
(Best Case Scenario)

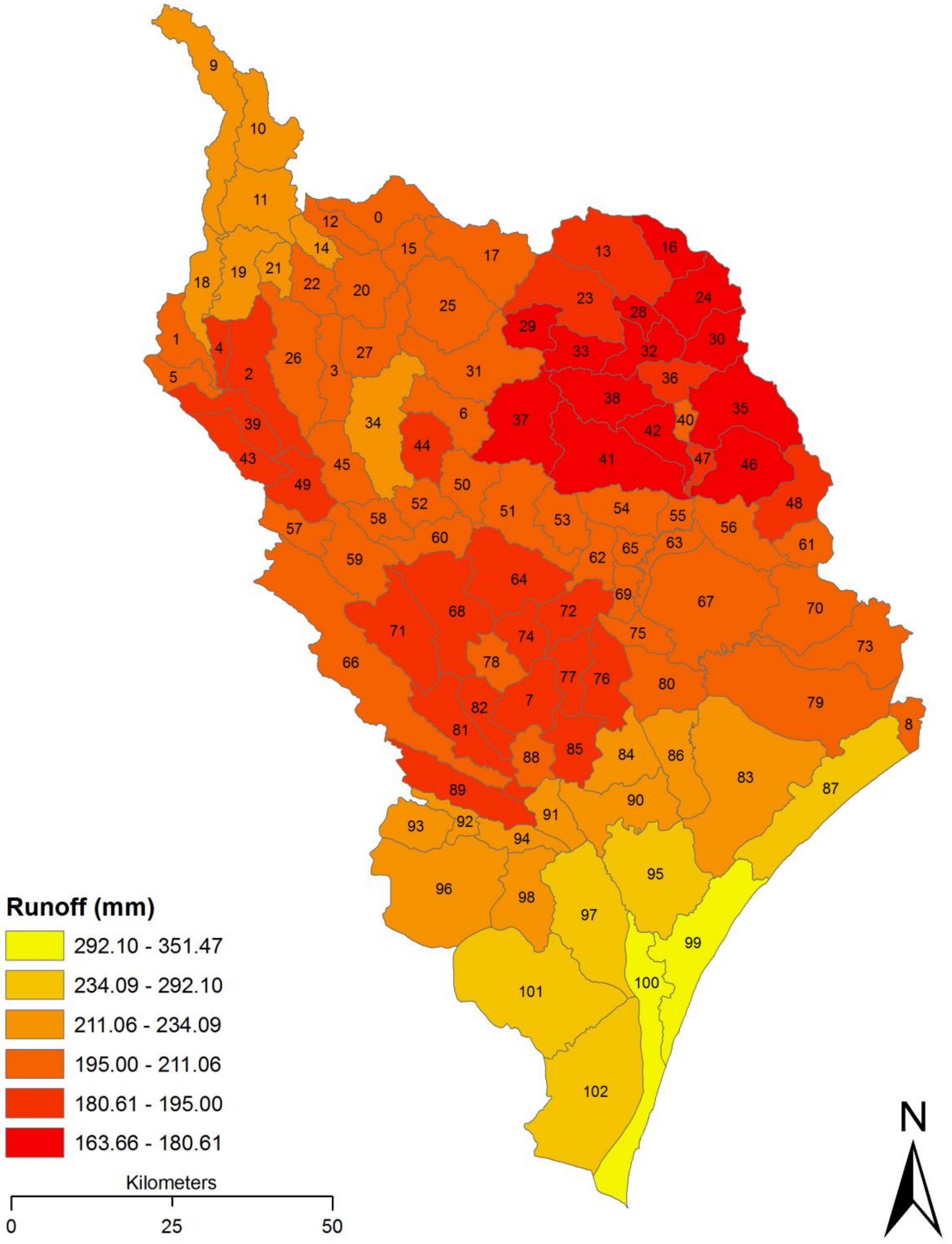
Source: Model Output (Best Case IPCC Prediction)



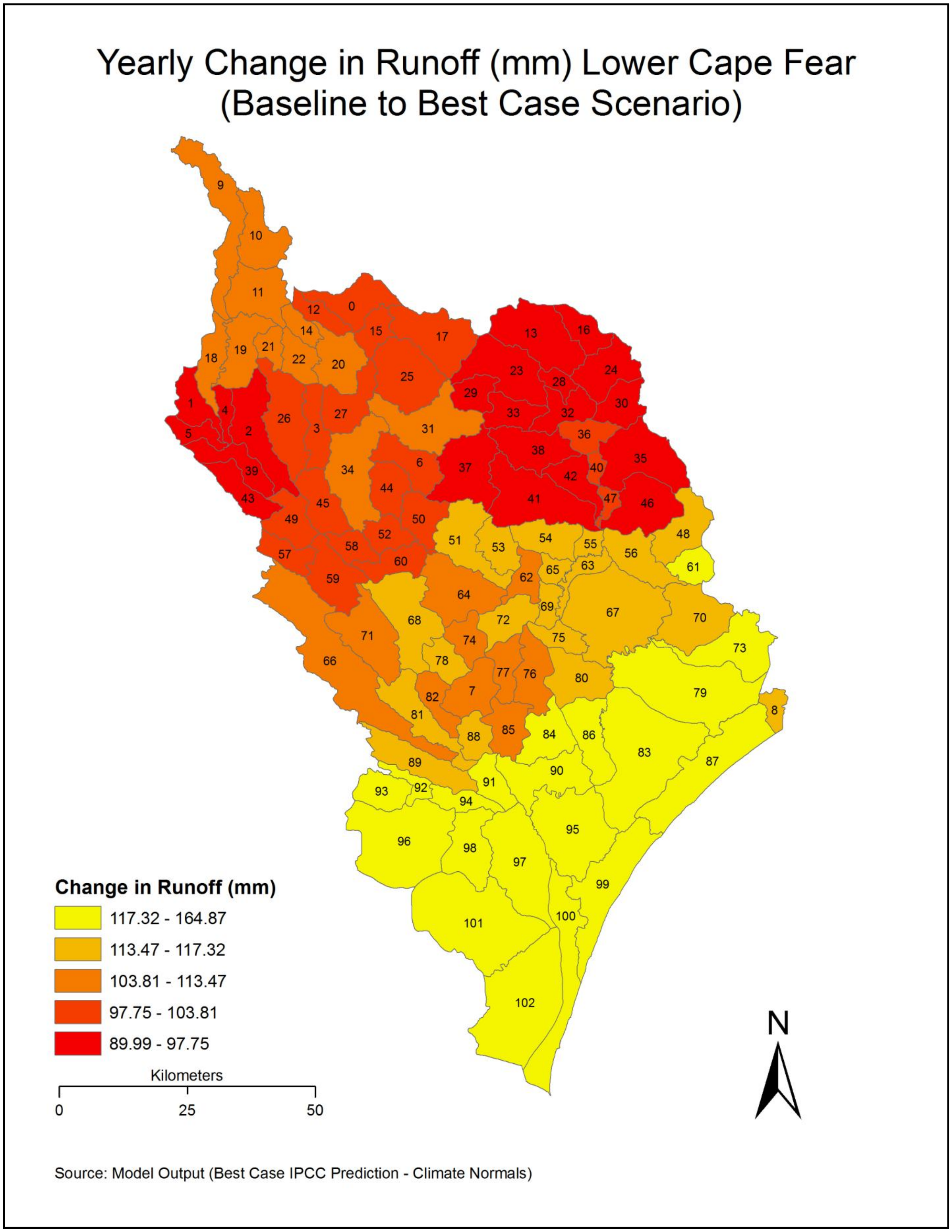
Yearly Runoff (mm) Lower Cape Fear
(Mean Case Scenario)

Source: Model Output (Mean Case IPCC Prediction)

Yearly Runoff (mm) Lower Cape Fear
(Worst Case Scenario)

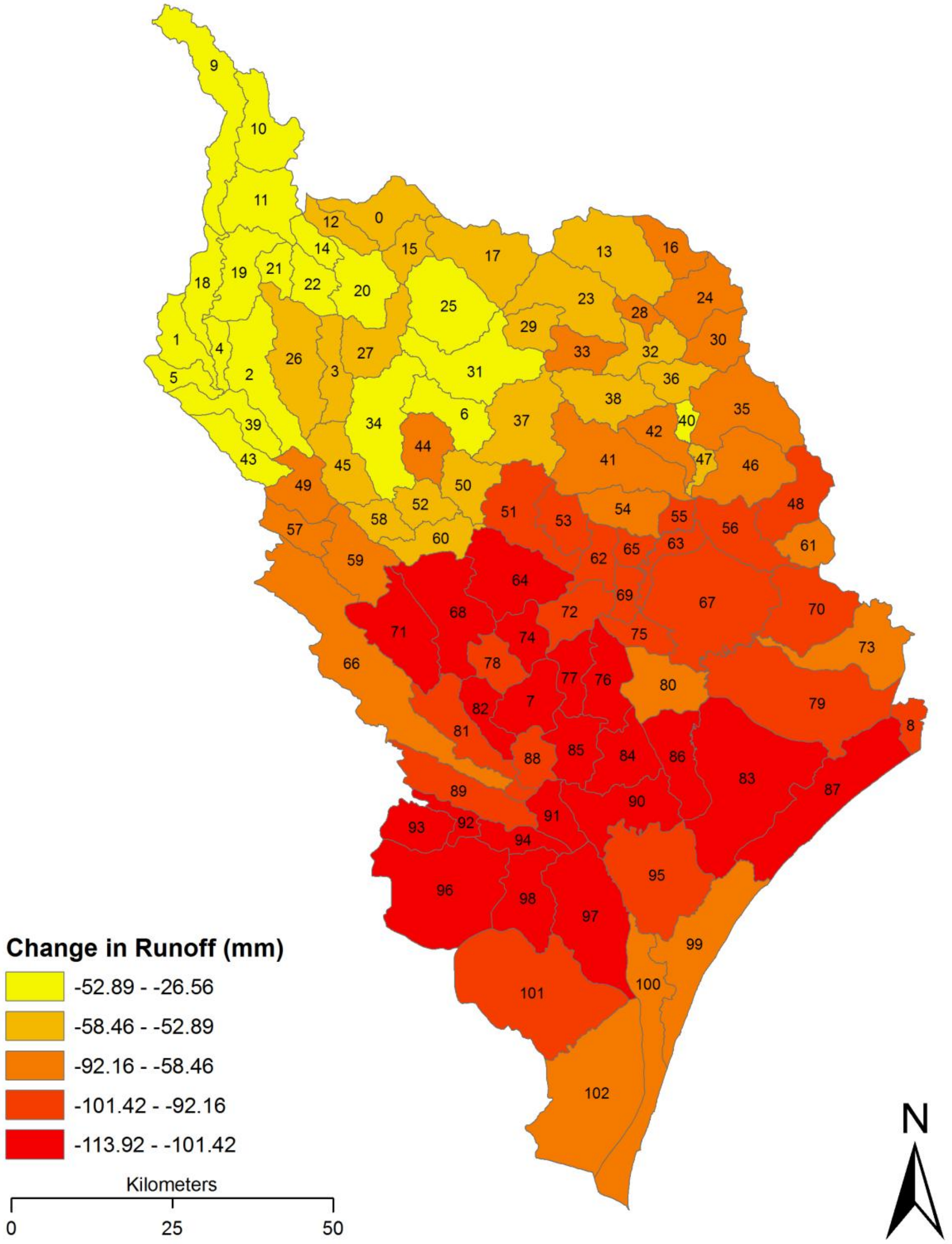


Source: Model Output (Worst Case IPCC Prediction)


Yearly Change in Runoff (mm) Lower Cape Fear
(Baseline to Best Case Scenario)

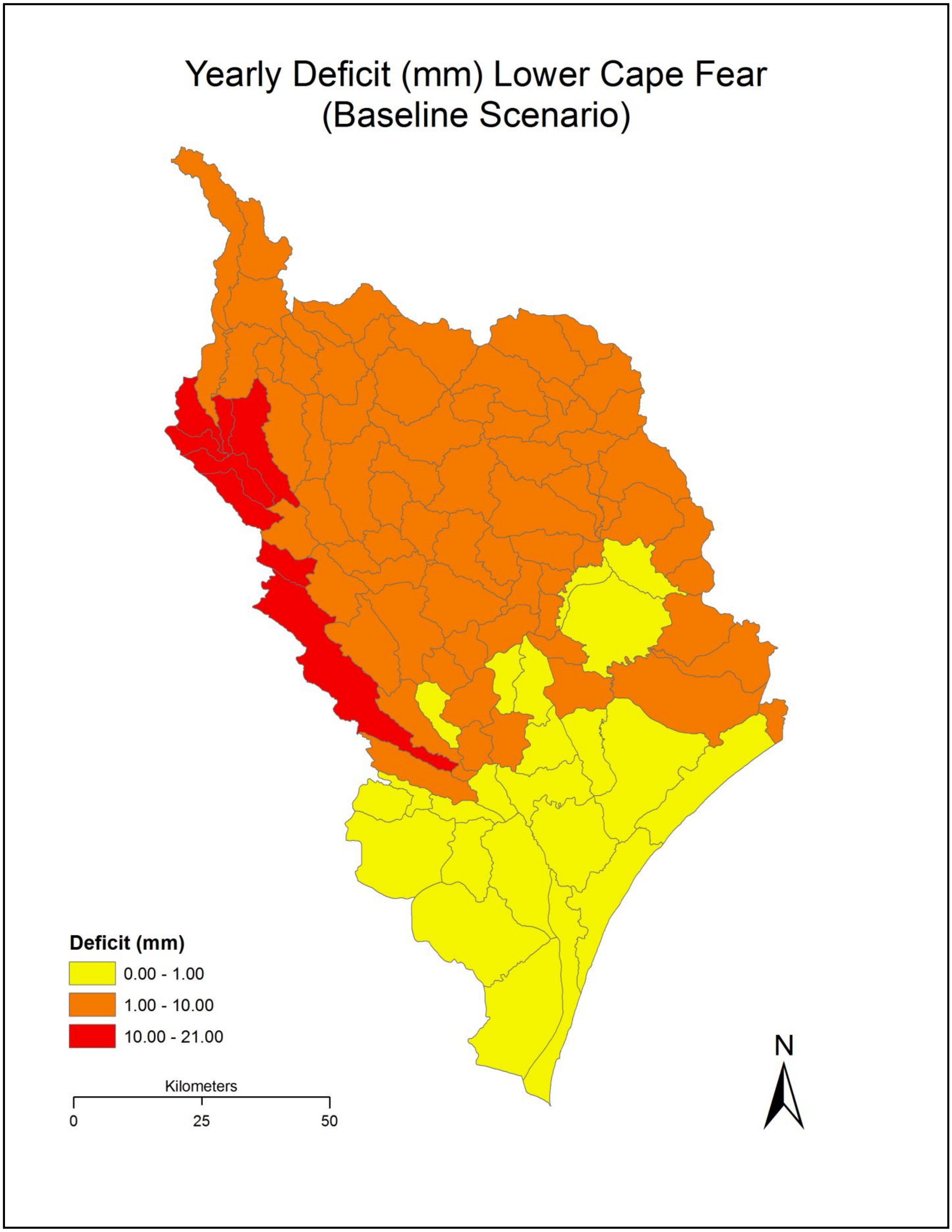
Source: Model Output (Best Case IPCC Prediction - Climate Normals)

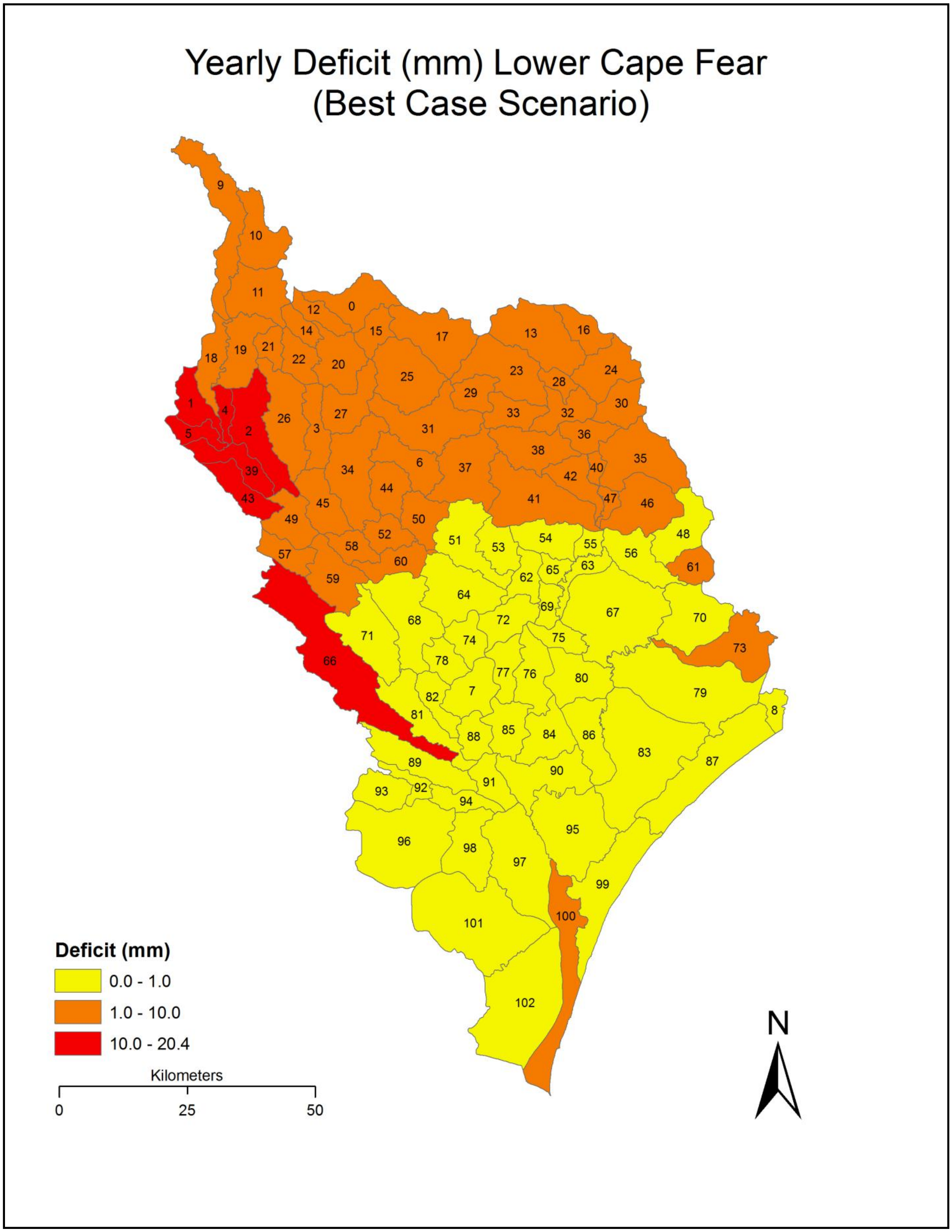
Yearly Change in Runoff (mm) Lower Cape Fear
(Baseline to Mean Case Scenario)

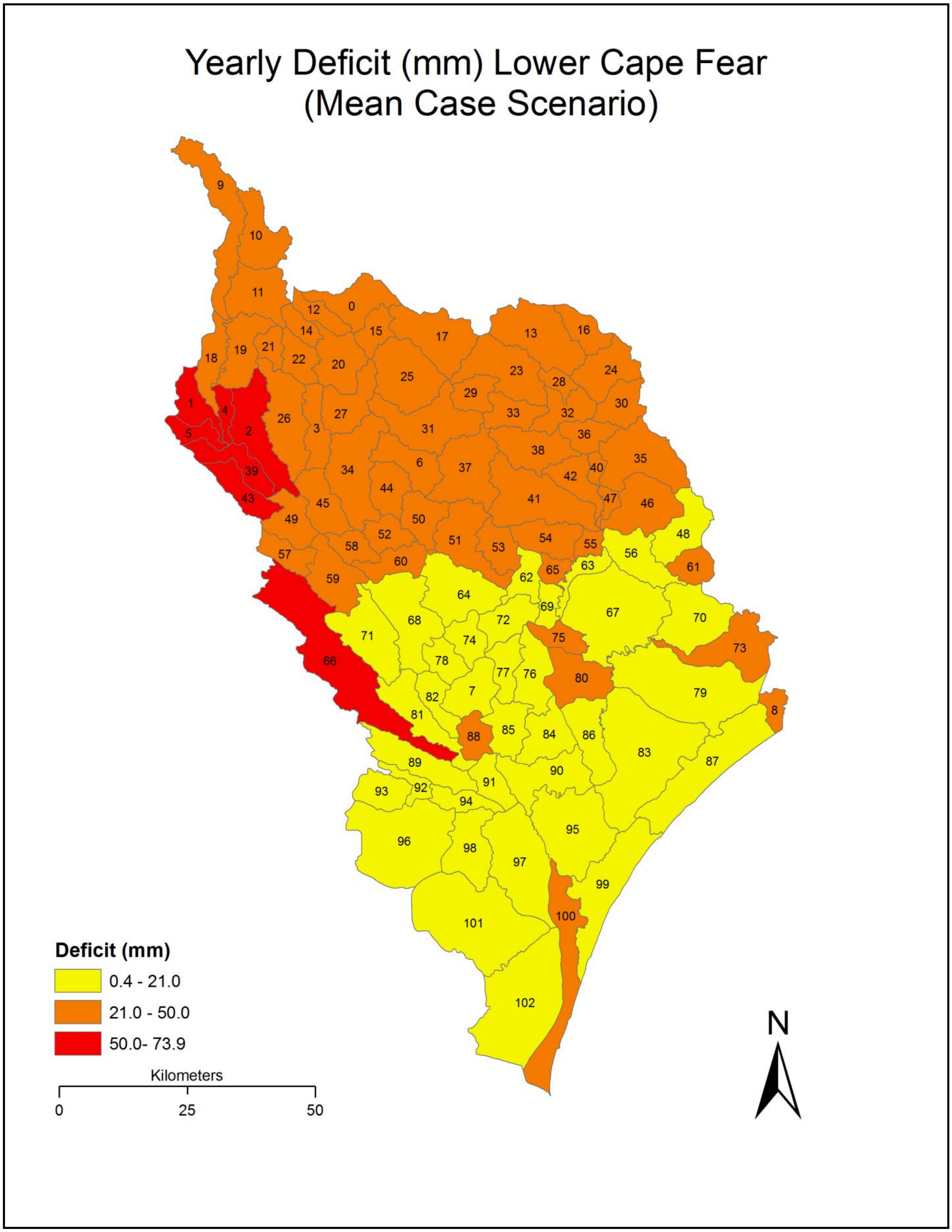


Source: Model Output (Mean Case IPCC Prediction - Climate Normals)

APPENDIX B: MODEL OUTPUT FOR DEFICITS




Yearly Deficit (mm) Lower Cape Fear
(Best Case Scenario)


Yearly Deficit (mm) Lower Cape Fear
(Mean Case Scenario)
9
10
11
12
0
14
15
17
13
16
18
19
21
22
20
25
23
28
24
29
30
1
4
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26
3
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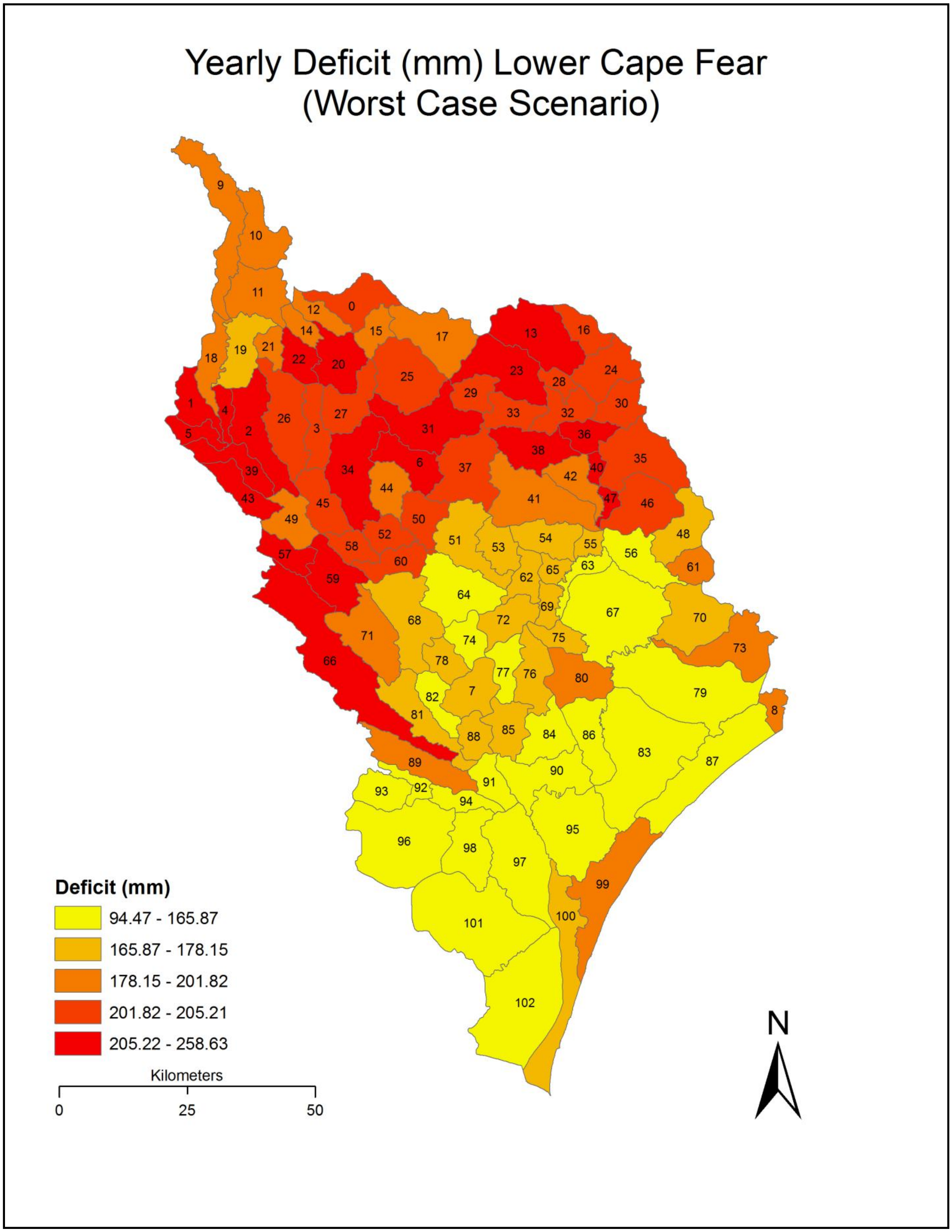
95
96
98
97
99
100
101
102
Deficit (mm)
🟨 0.4 - 21.0
🟧 21.0 - 50.0
🟥 50.0- 73.9
Kilometers
0
25
50
N


Yearly Deficit (mm) Lower Cape Fear
(Worst Case Scenario)
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11
12
0
14
15
17
13
16
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21
22
20
25
23
24
28
29
1
4
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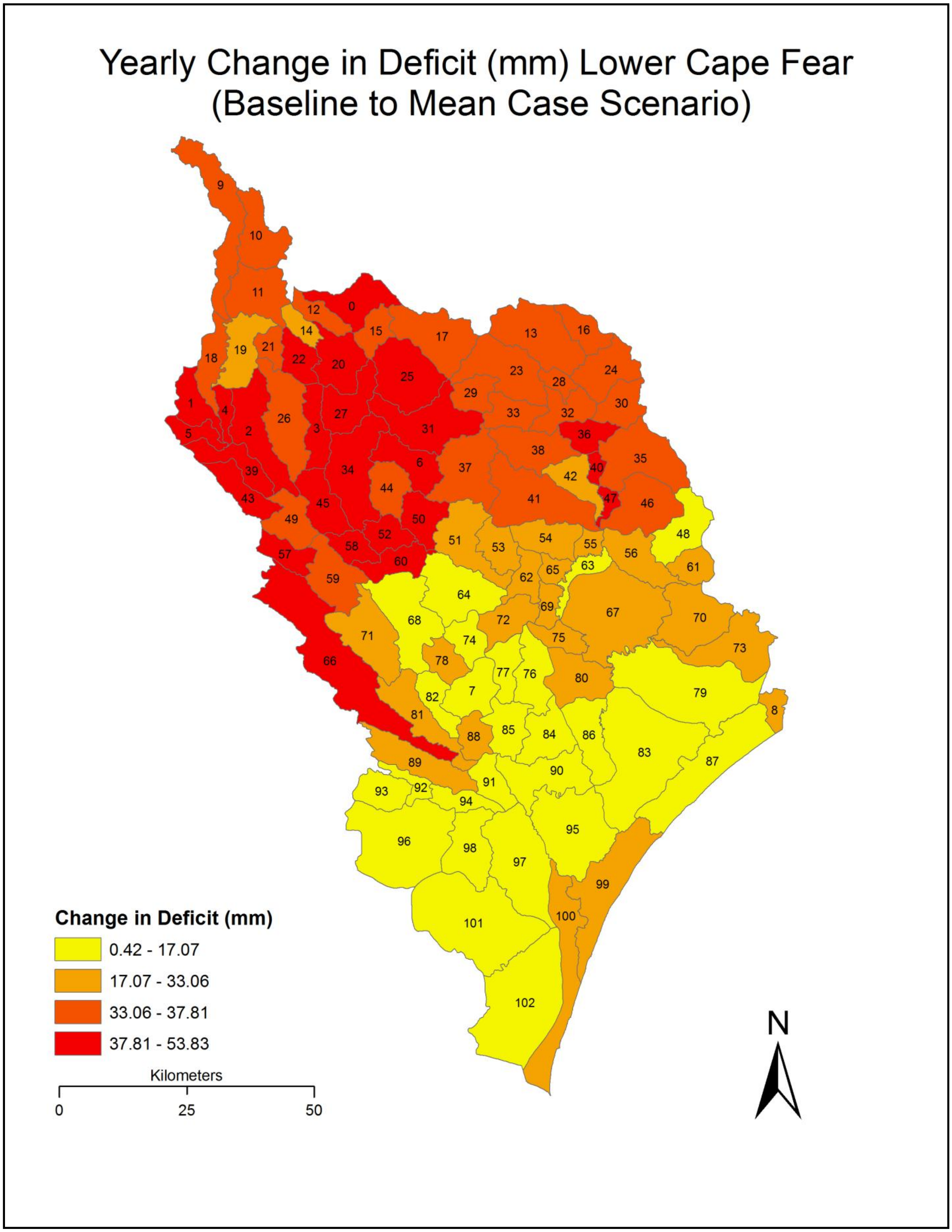
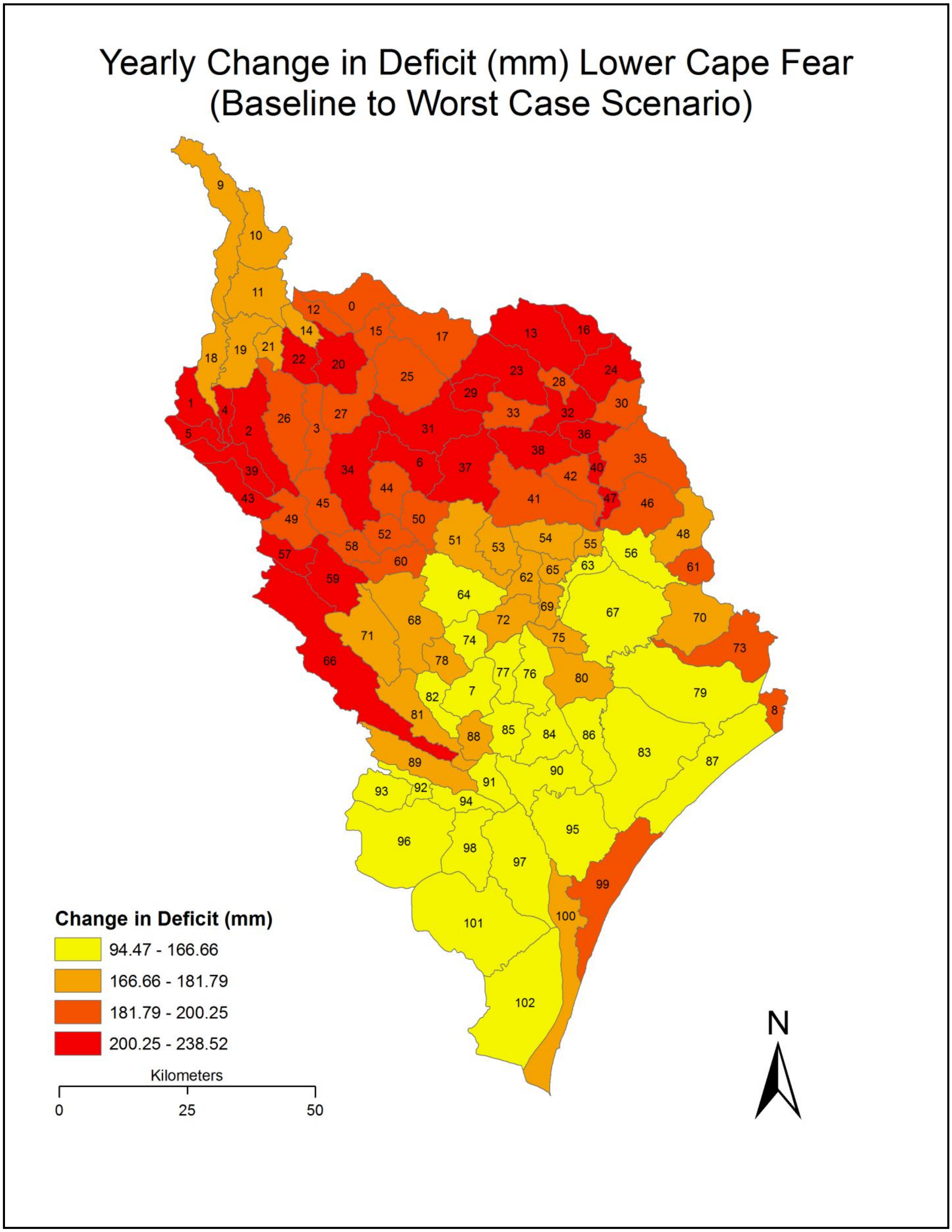
95
96
98
97
99
100
101
102
Deficit (mm)
94.47 - 165.87
165.87 - 178.15
178.15 - 201.82
201.82 - 205.21
205.22 - 258.63
Kilometers
0
25
50
N



Yearly Change in Deficit (mm) Lower Cape Fear (Baseline to Mean Case Scenario)


Yearly Change in Deficit (mm) Lower Cape Fear
(Baseline to Worst Case Scenario)
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98
97
99
100
101
102
Change in Deficit (mm)
94.47 - 166.66
166.66 - 181.79
181.79 - 200.25
200.25 - 238.52
Kilometers
0
25
50
N