Urban Water Availability and Potential Future Stressors: A Case Study of Raleigh-Durham, North Carolina

By

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The line that once existed between geographic regions that are considered “water poor” and “water rich” is now being blurred. Water managers in “water rich” regions, such as the Southeastern United States, are starting to realize that their abundant water supplies are not limitless. This holds true for North Carolina due to its current and future situation with regard to projected population growth, potential industrial demand changes, and impacts of climate change. Cities near Research Triangle Park (RTP), specifically Raleigh and Durham, have seen and will continue to see rapid population growth well into the mid-21st century. Available water supplies are predicted to be unsupportive of a growing Raleigh as early as 2040 and of Durham as early as 2050. This thesis addresses how these factors could impact water availability in the future. Different population projections are used to model the impact of residential water demands on water availability. Industrial demand change is modeled by the addition of hydraulic fracturing (fracking) to North Carolina, which was legalized in 2012. The water demand data for fracking from the Marcellus shale is used to develop projections for the increased industrial water demands from fracking. Historical stream flow and hydrograph data show past water availability which is used to model how stream flow could be altered in the future due to variation in precipitation patterns because of climate change. Ultimately population growth has

the biggest impact on water supply. Climate change has the potential to increase or decrease supply; however, an increase in supply is not enough to combat the high water demands of a growing population. Hydraulic fracturing also adds stress to the system, but the severity of the stress depends on the number wells and the specific amount of water needed to “frack” each well. In combination, these three factors have a substantial impact on water availability in Raleigh-Durham. Overall, regardless of the scenarios in this research with regard to population growth, climate change, and increased industrial demands, Raleigh and Durham will face a shortage of water availability in the future.

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CHAPTER 1: INTRODUCTION

The classical conception of available fresh water resources has been linked to regional climate types. The perceived notion about available water resources is that dry, arid climates, such as the American Southwest, have much less available water compared to wet, humid climates, such as the American Southeast (Vorosmarty et al., 2000). Water poor and water rich is another common description of such regions. These classical conceptions are currently under scrutiny and are being reassessed due to three main reasons. First, populations and thus different water using sectors are growing in many regions, which are increasing the demand for fresh water. Second, current predictions of climate change show that the increase of carbon dioxide in the atmosphere could alter the hydrologic cycle, which could tamper with patterns of how and when precipitation recharges surface and groundwater resources. To further complicate the situation, industrial demands for water are increasing substantially in some locations. These potential impacts on water resources may have both social and environmental implications that make planners and policy makers in different regions rethink how they can meet all the water demands in a sustainable fashion both currently and into the future.

Different water using sectors require different amounts of water. However, currently they have something in common: the demand for more water, stemming from a growing population on the global scale. These increases in water demands in the different sectors hold true for the United States. Within the United States, the sectors that use the most water are thermoelectric energy production, irrigation, and public supply (domestic use) (National Atlas, 2013). Population growth is the main driver of increasing water demand in each sector. As the population grows, there are more people who need water, and therefore, public supply demands increase, as do demands for energy. This also hold true for agriculture and industry. As population grows, there is an increasing demand for food, which requires more water resources. Likewise, a larger population creates more industrial demand, which in turn requires more water to meet that demand.

Climate change is also projected to impact water resources. Since the Industrial Revolution in the mid 19th century, the burning of fossil fuels has led to increased amounts of carbon dioxide being emitted into the atmosphere, adding more carbon dioxide than can be absorbed back into the earth's surface or by plants. Carbon dioxide is known as a "greenhouse gas," because it has the ability to trap heat. With more carbon dioxide in the atmosphere, heat radiated from the Earth's surface is more likely to be trapped than it is to be radiated back into space, with effects on the hydrologic cycle. Specifically, in some locations, climate change is predicted to cause less frequent delivery of precipitation to the Earth's surface, but these events are expected to be greater in magnitude when they occur (Intergovernmental Panel on Climate Change (IPCC), 2013). This could mean inadequate and infrequent recharge of water resources. With fewer precipitation events, the times between surface and groundwater recharge will be increased, which may deplete available supplies. Furthermore, more intense precipitation events, when they do happen, will lead to higher peak flows in surface waters and less ground water percolation, which will decrease groundwater recharge.

With these potential challenges facing available water resources, a systematic approach needs to be used to evaluate current available water in urban areas and the potential state of water resources in the future. The previously mentioned possible impacts need to be studied both in individual and in combined contexts. The individual context addresses how each factor will independently impact water availability, whereas the combined contexts address how each factor (population growth, climate change, and industrial demand changes), when applied to the others, will impact water resources. Such an approach will inform decision makers precisely which individual factors have the greatest effect on available water, but will also show how these impacts could affect water supplies in a coupled fashion.

As stated above, one of the individual factors is an increase in domestic water demands due to population growth. A key issue in water resources management, particularly in urban centers, is the way that population impacts the management of water resources. The first component of this research, then, is to determine how a growing population will affect water availability. If the local water supply stays the same, but the population is growing rapidly, the amount of available water for each person will decrease. This may have social implications because, as water availability decreases, the amount of water per person decreases. A strain in water availability could result in water restrictions or may result in not having sufficient water availability to adequately meet demand. This can also have environmental implications. The Clean Water Act and the Endangered Species Act have established water quantity minima for the maintenance of ecological systems. Increased demand for urban and industrial uses of water may threaten the maintenance of water quantity for ecological systems.

Along with the domestic (or residential) sector, it is necessary to look at the industrial sector in urban settings. As of now, manufacturing and energy production dominate water use in this sector. As the population grows, the demand for manufactured goods and energy output will continue to rise, which will increase demand on water resources. New industrial processes must be added to this equation. Thus, the second component of this research is to evaluate how an increase in current industrial water use and new industries could impact the amount of available water resources. New industries near urban centers can significantly increase industrial water needs.

Since about 2008, an industrial use that is particularly water intensive has become progressively more common in the United States. This new industrial water user is known as hydraulic fracturing, or “fracking.” The water intensive practices of hydraulic fracturing usually affect local and surrounding water supplies the most. Environmentally speaking, industrial water use usually has negative consequences with respect to water quality. In this research, hydraulic fracturing serves as the example of changing demands for industrial water supply in large part because of its rapid growth nationwide and its potential development in North Carolina. “Fracking” has large water requirements that often necessitate using distant sources. New industrial demands that have not been incorporated in past water demands may add more stress to water supply than is sustainable. Furthermore, the “fracking” process requires a substantial amount of personnel for the operation to work successfully. This usually brings in workers from outside the local community, which adds to the population and in turn increases water demand.

Both the industrial and domestic increases in water use are factors that can be determined with a certain level of confidence using historic water use data. Predicting how potential climate change could affect water resources is much more challenging. These predictions can be complicated because there are few tools that provide evidence about past climate change. Right now, a primary means for analyzing historic climate change is looking at ice cores, which show atmospheric compositions and snowfall accumulation from multiple millennia through glacial and interglacial periods (IPCC, 2013). However, these ice cores do not tell us the relationship between changing atmospheric temperatures and available water resources. The third part of this research is designed to analyze how potential climate change could impact water resources. If less frequent, more intense precipitation patterns do occur in the future, the potential for droughts will become more likely. These droughts have could have implications in both water poor and water rich regions. If droughts become persistent in more than just arid areas, urban areas could find themselves with diminished water resources that might not be able to meet demand adequately.

Individually these factors could have major implications on water availability, but it would be naïve to assume that any of these impacts will happen alone and not in a coupled fashion, in a given area. That is why the fourth component of this research is to evaluate how three factors could alter available water resources, in combination. It is likely that the combination of these three factors could have more far reaching and devastating effects on water resources than any of the factors would by themselves. Due to the necessity of water to human civilization, an integrated approach to see how water resources could be affected in the future is needed.

Ultimately, this research aims to address questions of how growing water demands and climate change could impact water availability in the future. Thus, the specific research questions are:

1. How will growing populations with higher water demands impact water availability and how will seasonal variability in water demands strain water supply?
2. How will climate change, in relation to changes in precipitation and temperatures, impact water availability in the future and how will climate change impact water supply on a seasonal scale?

3. How will increasing industrial water demands in the future affect water availability?
4. How will these three factors in combination impact water supply?

A review of the relevant literature is provided in Chapter 2 followed by a description of the study area (Chapter 3) and methodology (Chapter 4). The results from the analyzed data are outlined in Chapter 5 followed by conclusions in Chapter 6.

CHAPTER 2: LITERATURE REVIEW

There are multiple factors that impact water availability. However, this research focuses on three: population growth, climate change, and increasing industrial water demands. To better understand how these factors affect water supply and how water managers deal with each factor, this chapter is broken down into four section to provide a better understanding of each element. The four sections are 1. population growth, 2. climate change, 3. industrial water demand and hydraulic fracturing, and 4. urban water management.

Population Growth

Global population has dramatically increased since the beginning of the twentieth century. The population was 1 billion people in 1804 and doubled to 2 billion people in 1927. Since then, the population has exploded in a very short time, reaching 6 billion people in 1999. It took the population 123 years to double from one to two billion people, but only seventy-two years to triple from two billion people to six billion people (Population Division, 1999).

Cities and metropolitan areas (urban agglomerations) feel the stress of population growth most acutely. The major cities of the world have grown rapidly since 1950 and many others have become major cities (defined as population in excess of five million). In 1950, there were eight urban agglomerations with a population of at least five million, which were New York, London, Tokyo, Paris, Moscow, Shanghai, Buenos Aries, and Rhein-Ruhr North (an urban agglomeration around Essen, Germany). These eight metropolitan areas had a total combined population of 54.5 million people. Twenty-five years later, in 1975, there were twenty-two cities that had a population of at least 5 million and they had a total combined population of 195.2 million people.

In 2000, the number of major cities increased again, to thirty-nine, with a total combined population of 394.1 million people (Population Division, 2001).

The populations of major urban areas have increased by almost eight times between 1950 and 2000 and have just about doubled from 1975 to 2000. The projections for 2015 are that there will be fifty-eight major cities with a total combined population of 604.4 million people (Population Division, 2001). The city of Tokyo is a noteworthy example of rapid urban population growth. In 1950, Tokyo had the third largest population with 6.9 million people. It increased approximately five-fold to 32.5 million people by 1990, and is projected to still be the largest urban center with a population of 38.7 million people in 2025 (Population Division, 2011). The related demand on resources of these ever increasing urban populations presents a growing serious problem.

Population growth and expansion of urban agglomerations are trends that are also happening within the United States. In 1950, the population of the US was 152.27 million. Currently the population is 316.8 million, reflecting almost a doubling in 63 years (United States Census Bureau 2011, 2013). Furthermore, the percentage of Americans living in urban settings is increasing. In 1950, the percentage of American citizens living in urban areas was 63.9 percent, which grew to 77.4 percent in 2000. This trend is projected to continue with a 2030 urban population percentage of 84.5 (Population Division, 2001).

As the population grows, the available water per person will decrease unless new water supply sources are made available, which arise when the water supply per person falls below established thresholds. Water shortage is defined as having less than 100 liters of water per day per person for an urban population to live comfortable long-term. (McDonald et al., 2011a). There are two types of water shortages, perennial and seasonal. A perennial water shortage is when “annual water availability is less than 100 liters per day, per person,” and a seasonal shortage is when “monthly water availability is less than 100 liters per day, per person” (McDonald et. al, 2011a, pp. 6312-6313). In addition to increasing population, there are two other factors that contribute to urban water supply strain: aridity and pollution (McDonald et al. 2011b). Cities in arid climates must meet water demands by drawing from an environment in which water is scarce and replenishment is unpredictable. Water shortages due to aridity also arise seasonally (and over shorter periods) in environments not considered arid. Water pollution can put an additional strain on water supplies. For example, severe pollution upstream from a water treatment facility may render the source water untreatable, which would reduce available water supplies. As these factors combine, changes in any of them over time can exacerbate water supply issues (Gleick, 2003).

Climate Change

Since the Industrial Revolution, beginning in the 1850’s, carbon dioxide (CO_2) concentrations in the Earth’s atmosphere have led to global climatic changes, such as increasing atmospheric temperatures (IPCC, 1995). Industrialized countries burn fossil fuels, which emit CO_2, to provide energy. The emitted carbon dioxide is released into the atmosphere, increasing concentrations of atmospheric CO_2 compared to pre-1850 concentrations. Carbon dioxide absorbs longwave radiation emitted from the earth’s surface, a process known as “radiative forcing.” The “trapped” longwave radiation is the cause of the current climate change, sometimes known as the Greenhouse Effect (IPCC, 1995). Along with the Greenhouse Effect, changing land use patterns and deforestation across the globe also increase the warming of the Earth’s atmosphere. These changes in land use patterns are currently removing lighter surfaces, which reflect sunlight, and are being replaced with darker surfaces, which absorb sunlight (IPCC, 2013). The increasing amount of darker surfaces on the Earth's surface leads to more sunlight being absorbed by the Earth, which is then emitted back to the atmosphere as longwave radiation. More CO_2 in the atmosphere and the Earth emitting more longwave radiation have led to increasing global atmospheric temperatures, an outcome of which is climate change. However, it is important know to more than just the causes of climate change; more specifically, it is important to know the implications of climate change.

To better understand the potential impacts of climate change, the Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the United Nations. The IPCC has released 5 reports since its formation in which it has summarized the contemporary scientific knowledge of the causes and potential global implications of climate change. The two most recent reports, the Fourth Assessment Report (AR4) (IPCC, 2007) and the Fifth Assessment Report (AR5) (IPCC, 2013) state that current radiative forcing is largely due to increasing anthropogenic carbon emissions. Furthermore, both reports show how radiative forcing could impact future global temperatures and precipitation patterns. The current consensus on general temperature and precipitation trends is that warm climates will get slightly warmer and will have decreases in precipitation and that colder climates will see the largest increases in temperatures and will also experience increases in precipitation, along with the notion that arid climates will get drier and humid climates will get wetter (IPCC, 2007). However, these changes will differ from the global average from region to region. The change in temperature is projected to alter the water cycle in some places. This alteration is known as an "accelerated" water cycle, which could have implications on water resources and water availability.

An accelerated water cycle refers to a shift in the current conditions of the water cycle, in which warmer temperatures allow for increased evaporation and precipitation rates (Trenberth, 1999; Huntington 2006). Allen and Ingram (2002) argue that increased precipitation rates are not the product of the ability of the atmosphere to hold more moisture, but rather are the result of higher energy availability. Higher energy availability allows for more water to be evaporated and gives the atmosphere the ability to hold more moisture because higher available energy allows for higher temperatures (Muller et al., 2011). This could lead to heavier precipitation events due to more available water vapor able to be precipitated. Therefore, the shift in the water cycle into an accelerated form could lead to more frequent droughts and floods, because of a change in precipitation patterns.

Fewer, but heavier rain events could produce the same amount of rain over an annual period. However, fewer precipitation events suggest reduced overall water volumes for recharging surface and ground water supplies. The more time that passes between rain events, there is less surface water available and less groundwater recharge over time (Milly et al., 2005). If inadequate recharge persists, local or regional government may declare an area to be in a drought. From a hydrologic perspective, droughts occur when water supplies drop below established thresholds (United States Geological Survey, 2013) (Table 2.1). A drought may be minimal, where the effects are barely noticeable to the population, or a drought can be severe, where the local water supply is not able to meet established thresholds (e.g., 100 liters per day, per person). Also, increased evaporation rates can intensify droughts. Specifically, increased evaporation rates can cause a decrease in water availability because surface waters could evaporate faster than they can be tapped to meet demand, which could cause water shortages (Lowe et al., 2009).

Drought Type	Description
Meteorological	A deficiency in precipitation relative to normal conditions (generally the first manifestation of drought.)
Agricultural	Low soil moisture (caused by meteorological drought) leading to negative impacts on crop growth.
Hydrologic	A decrease in surface water flow and groundwater levels due to the cumulative effects of meteorological droughts.
Socioeconomic	Socioeconomic impacts associated with meteorological, agricultural, or hydrological droughts.

Table 2.1**.** Drought Types and Definitions (Anisfeld, 2010).

Increased flooding is also a projection of climate change (Vicuna and Dracup, 2007) due to more intense precipitation events (Trenberth, 1999). Intensified events will lead to greater runoff and potentially flash flooding (Arnell, 1999). During light precipitation events that happen over a long period of time, precipitation is able to be absorbed by the ground (to replenish ground water) or is able to slowly collect in streams or lakes (surface water) over time. These precipitation events let water replenish both surface and ground water. In intense precipitation events that take place very quickly, water is not able to be absorbed into the ground before it pools and instead starts to run off. In addition, the quantities of water will cause streams and lakes to swell very quickly, which can cause flash flooding. Both of these situations do not replenish water supplies (both surface and ground water) adequately (Vicuna and Dracup, 2007).

In both AR4 and AR5, the Fourth and Fifth Annual Reports (IPCC, 2007; 2013), respectively, there is a focus on projected climatic change variability to different regions, with AR5 showing both temperature changes (Figures 2.1 and 2.2) and precipitation changes (Figures

2.3 and 2.4) for the globe through three different periods of 20 years within the time frame of 2013 to 2100. These projections are based on representative concentration pathways (RCP) 4.5. RCP is used because it is the mean model for temperature and precipitation change in the future, and is based on 42 different climate models, which give a range of projections for temperature and precipitation change in the future. In Figures 2.1-2.4, the column on the left is the 25th percentile value of RCP 4.5, the middle column is the 50th percentile value, and the column on the right is the 75th percentile value. Percentiles are based on the range of the 42 climate models to produce RCP 4.5. For example, the 50th percentile values mean that of all the models run, 50% of the resulting values were less than or equal to the 50% output value from the models. This is the same procedure for the 25th and 75th percentile values also. Thus, more warming is shown in the 75th percentile maps than on the 25th percentile maps. It can be seen that the most warming will happen in areas in closer proximity to the poles and less warming will happen in areas closer in proximity to the equator. Furthermore, warming is projected to occur to a much higher degree in winter months than in summer months. Projections for precipitation changes suggest that on average, mid latitudes will experience a decrease in precipitation and that the equator and the poles will experience increases in precipitation. However, these averages vary depending on the type of climate, which can be seen within the United States.

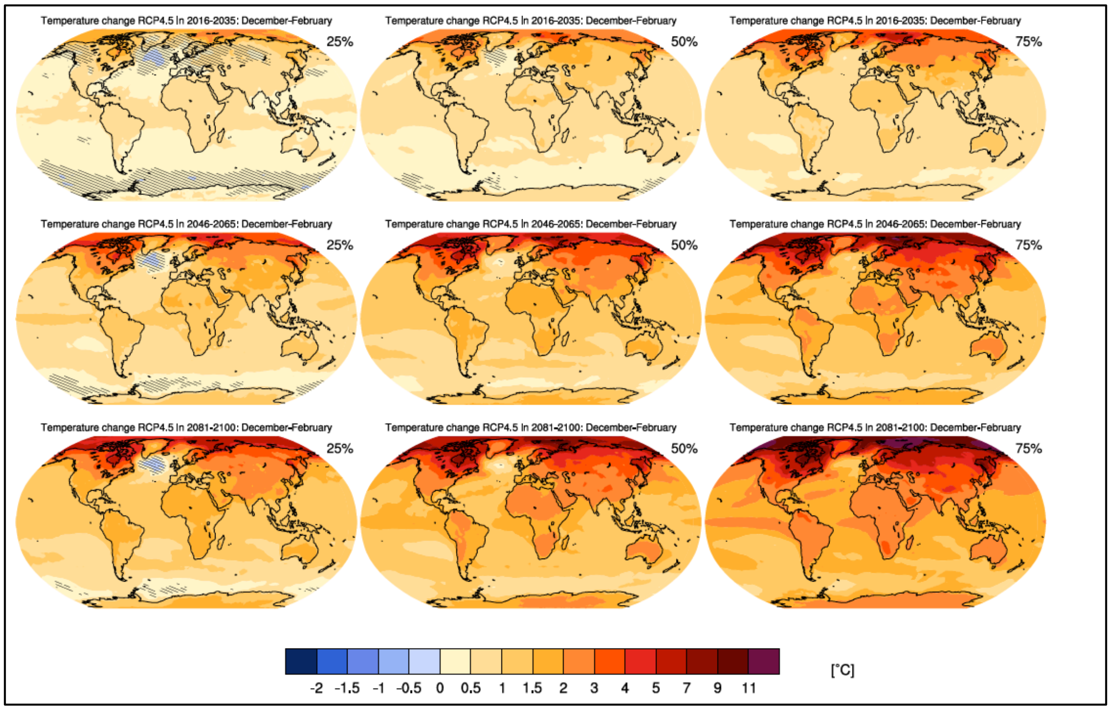


Figure 2.1**.** Global Temperature Change Projections in Winter Between 2013 and 2100 (IPCC, 2013).

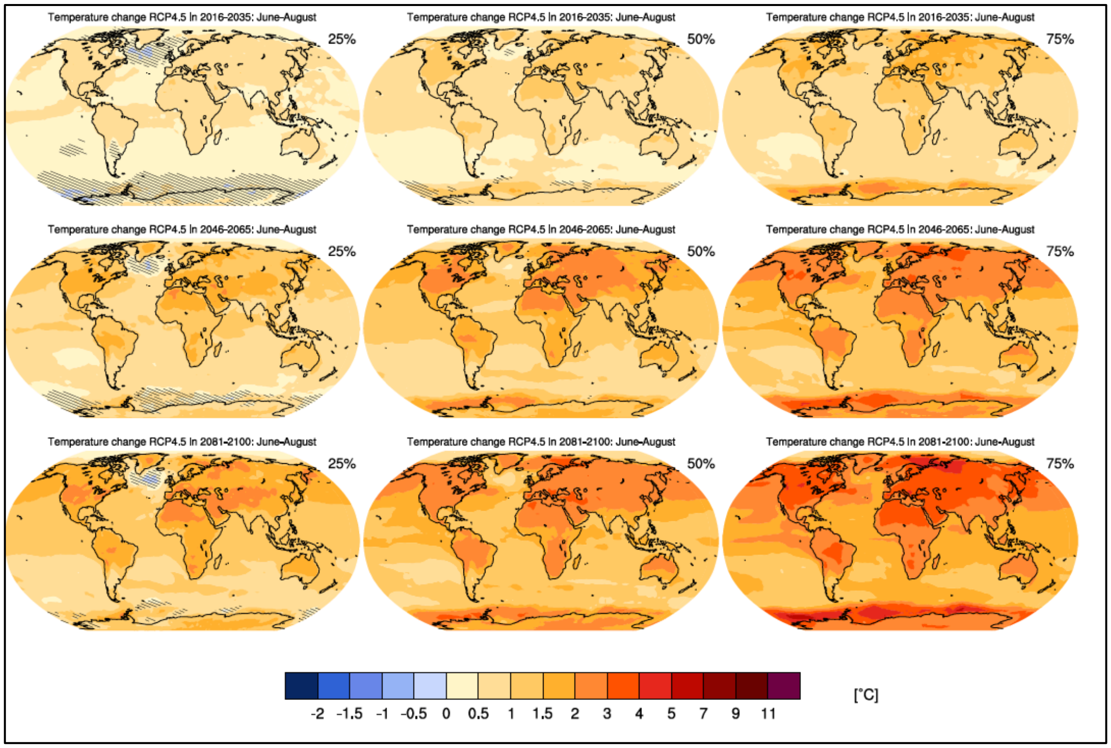


Figure 2.2. Global Temperature Change Projections in Summer Between 2013 and 2100 (IPCC, 2013).

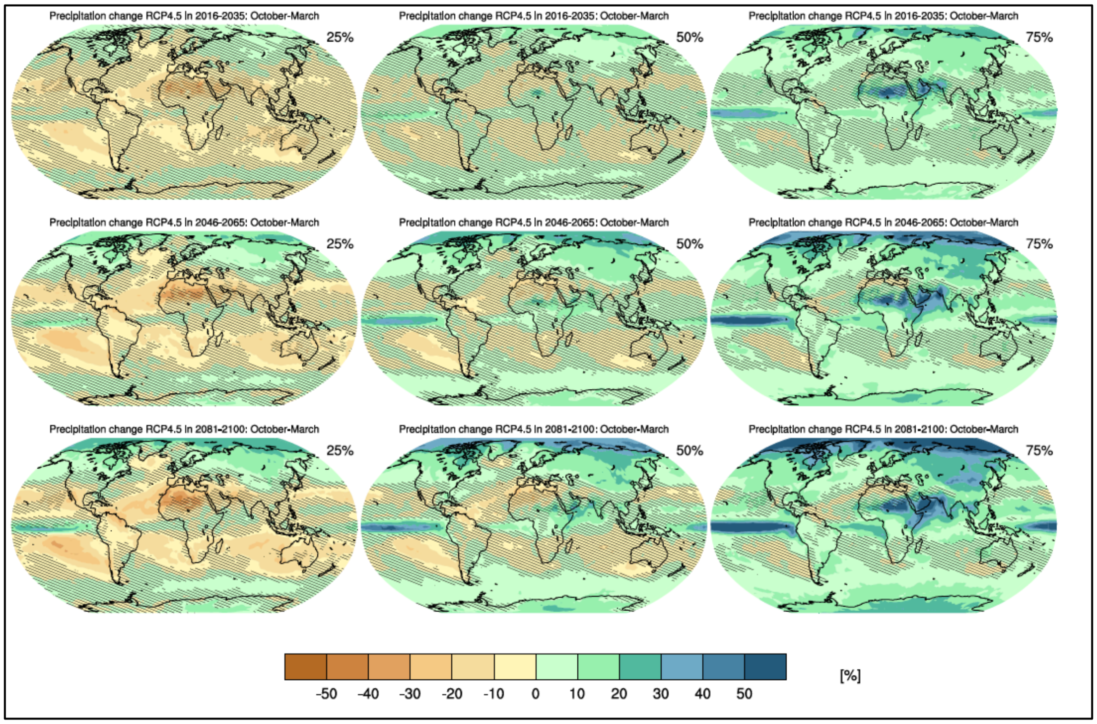


Figure 2.3. Global Precipitation Changes Projections in Winter Between 2013 and 2100 (IPCC, 2013).

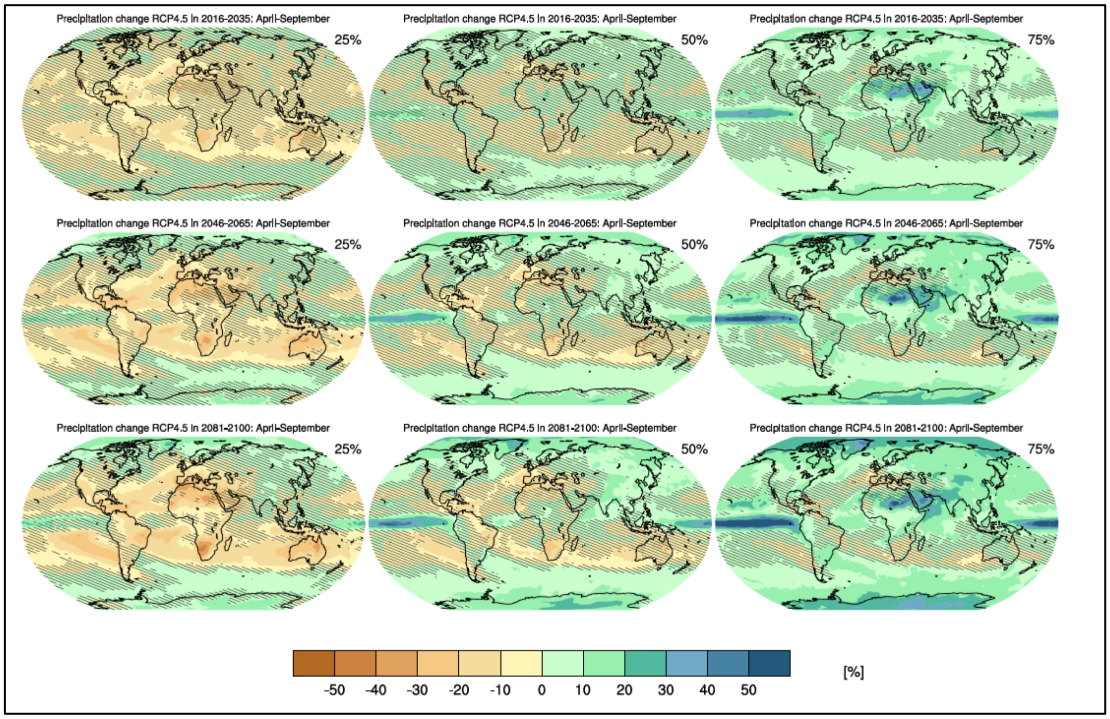


Figure 2.4. Global Precipitation Changes Projections in Summer Between 2013 and 2100 (IPCC, 2013).

The AR5 report presents projections for two regions within the United States, the West region and the East region. Within each region, the effects of climate change on temperature and precipitation vary. With respect to the East region, the expected temperature increase is different for the Southeastern United States, New England, and North Canada (Figures 2.5 and 2.6). These regions also vary with respect to the projected change in precipitation (Figures 2.7 and 2.8). Based on the projections of AR5, the Southeast could see an increase of 3°C and a 20 percent increase in precipitation (AR5, 2013). According to AR5, wet areas will get wetter, and dry areas will get drier. This means that the Southeast will receive more rain; however, it is impossible to pinpoint exactly if more rain will be delivered under current precipitation paradigms or under the influence of an accelerated hydrologic cycle (Sun et. al, 2008; Bastola, 2013).

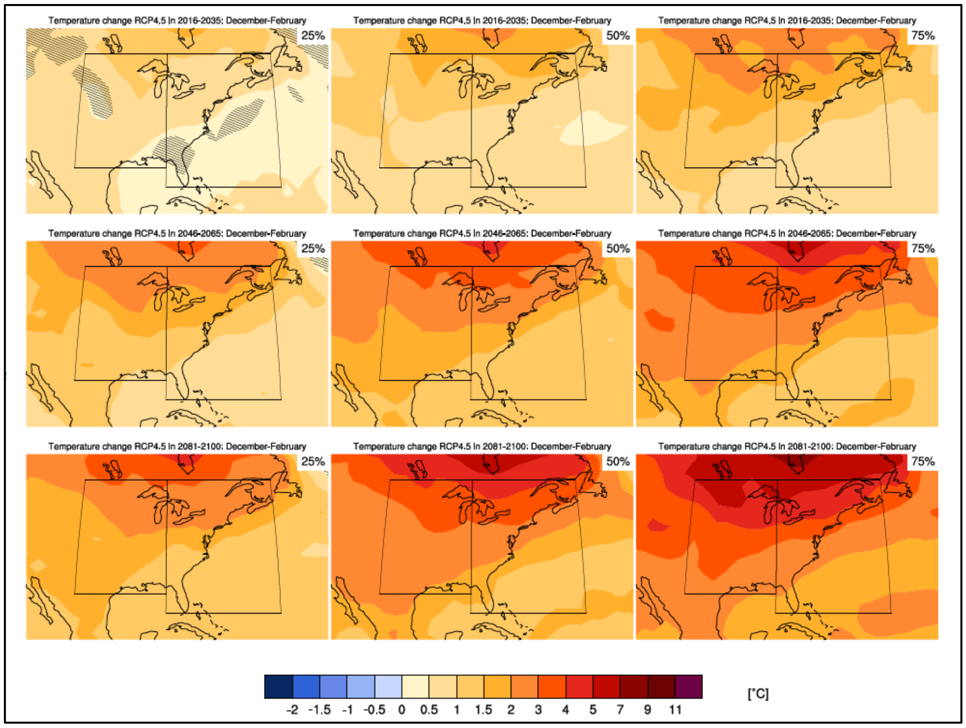


Figure 2.5. East Region of USA. Winter Temperature Change Projections for 2013- 2100 (IPCC, 2013).

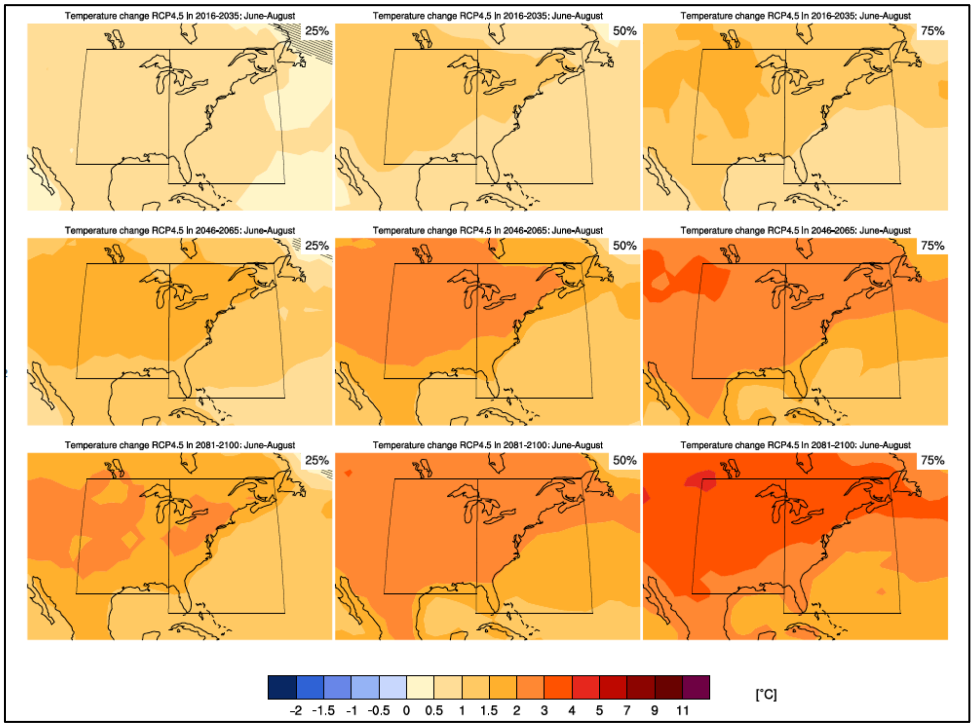


Figure 2.6**.** East Region of USA. Summer Temperature Change Projections for 2013- 2100 (IPCC, 2013).

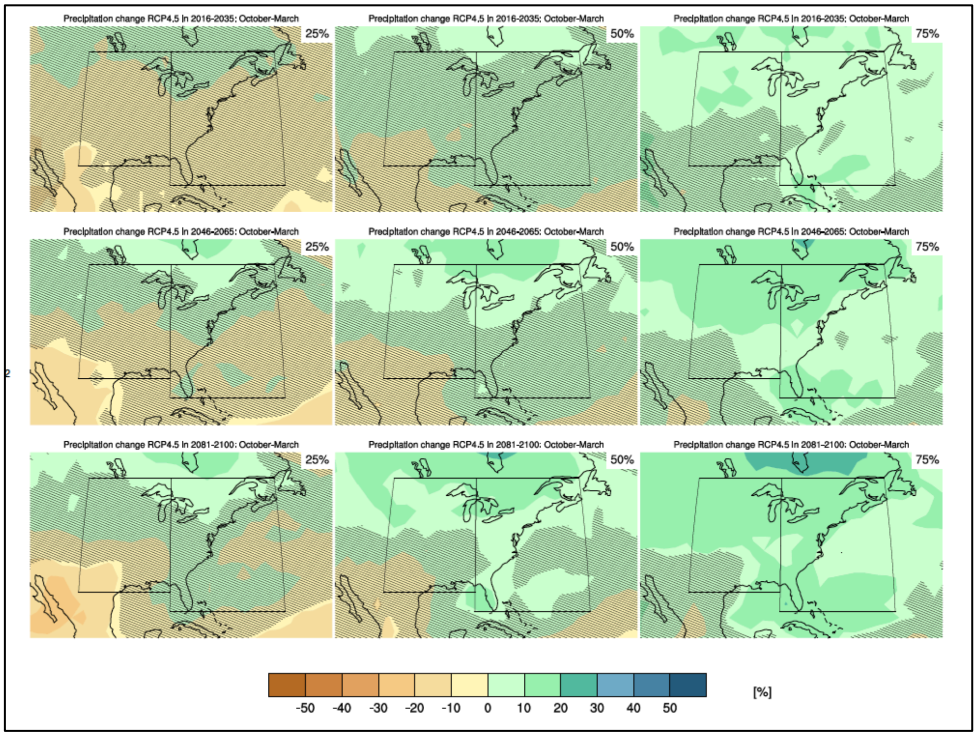
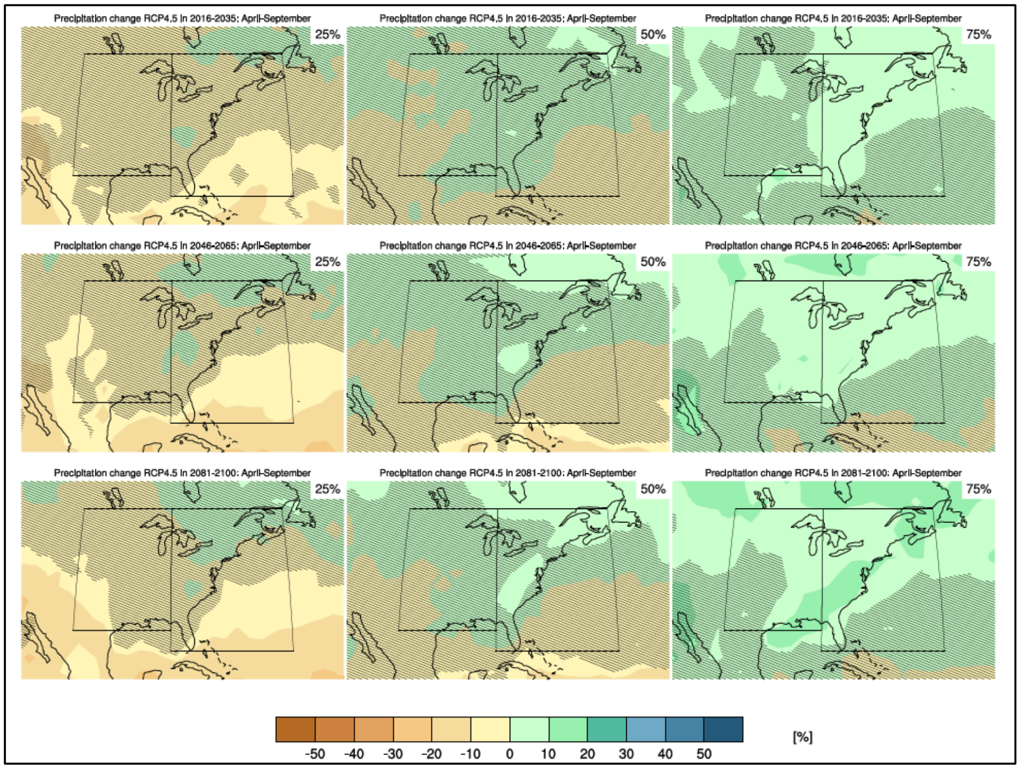


Figure 2.7**.** East Region of USA. Winter Precipitation Change Projections for 2013- 2100 (IPCC, 2013).



Precipitation change RCP4.5 in 2016-2035: April-September

Precipitation change RCP4.5 in 2046-2065: April-September

Precipitation change RCP4.5 in 2081-2100: April-September

Figure 2.8. East Region of USA. Summer Precipitation Change Projections for 2013- 2100 (IPCC, 2013).

Industrial Water Demand and Hydraulic Fracturing

As mentioned before, the three major water-consuming sectors in the United States are thermoelectric energy production, irrigation, and public supply (domestic use) (National Atlas, 2013). However, the mix of major water consuming sectors may be different at the state and local level. Urban areas are dominated by domestic and industrial uses, as well as energy related water use such as thermonuclear and hydroelectric energy (Voinov and Cardwell, 2009). The competition between domestic use and use for energy production in urban areas can be a complicated water supply issue.

According to the United States Geological Survey (USGS, 2014a), the types of industries that are major users of water are metal producers, wood and paper producers, chemicals, gasoline, and oils. These industries use water mainly for fabricating, processing, washing, diluting, cooling, or transporting a product. However, total withdrawals of water for industrial use in 2005 comprised about 4 percent of the total national average of water withdrawals (Figure 2.9).

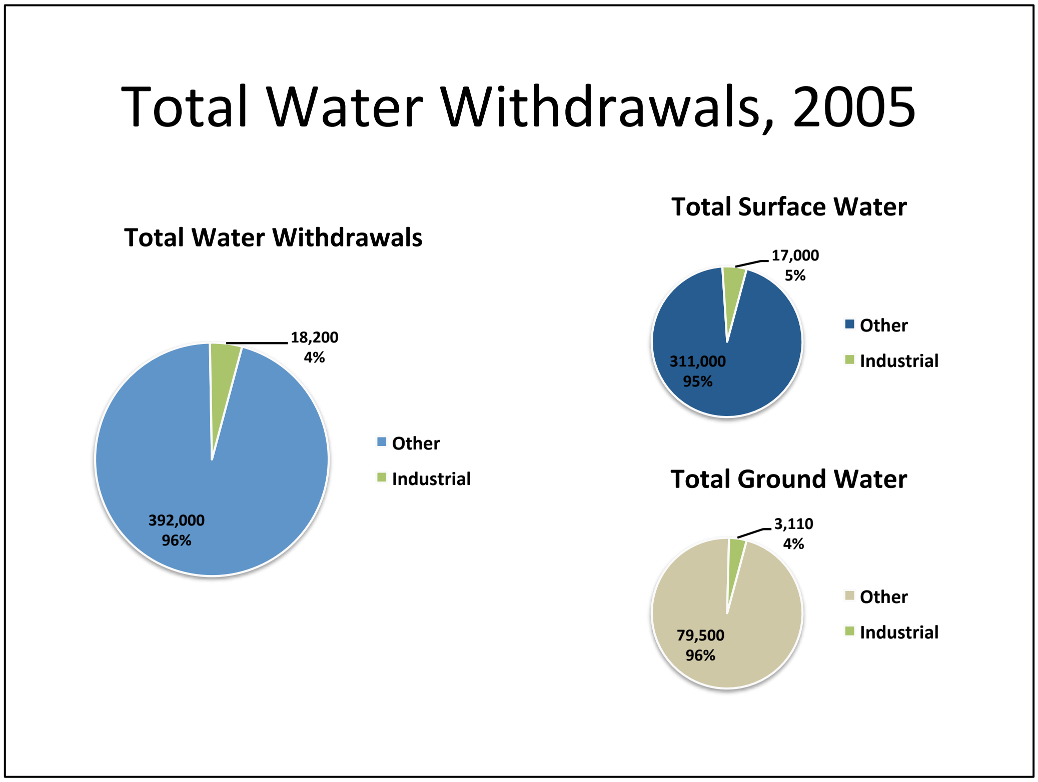


Figure 2.9. Total and Industrial Water Demands in 2005 (USGS, 2014a).

Industrial water demands are increasing in the United States. One reason for this increase is the emergence of hydraulic fracturing, which is a water-intensive practice of extracting trapped natural gas from deep, underground shale beds (Kargbo et al., 2010). There are two major reasons why natural gas and its production have come to the forefront of national attention. First, the production of natural gas makes the United States less dependent on foreign oil. “Of the natural gas consumed in the United States in 2011, about 95% was produced domestically; thus, the supply of natural gas is not as dependent on foreign producers as the supply of crude oil, and the delivery system is less subject to interruption” (US Energy Information Administration

(EIA), 2012) Second, natural gas is more environmentally friendly than coal and oil, which are currently the main fuel sources in the United States. “The combustion of natural gas emits significantly lower levels of carbon dioxide and sulfur dioxide than does the combustion of coal or oil. When used in efficient combined-cycle power plants, natural gas combustion can emit less than half as much carbon dioxide as coal combustion, per unit of electricity output” (US EIA, 2012).

The growth and popularity of natural gas use have risen greatly in the United States because of a new application of a drilling technique that makes shale gas economically viable to extract. In the past, shale gas was not economically viable to extract due to the limitations of vertical drilling production rates. “Horizontal drilling provides more exposure to a formation than does a vertical well. This increase in reservoir exposure creates a number of advantages over vertical well drilling. Six to eight horizontal wells drilled from only one well pad can access the same reservoir volume as sixteen vertical wells” (U.S. Department of Energy, 2009, pg. ES-3,) (Figure 2.10).

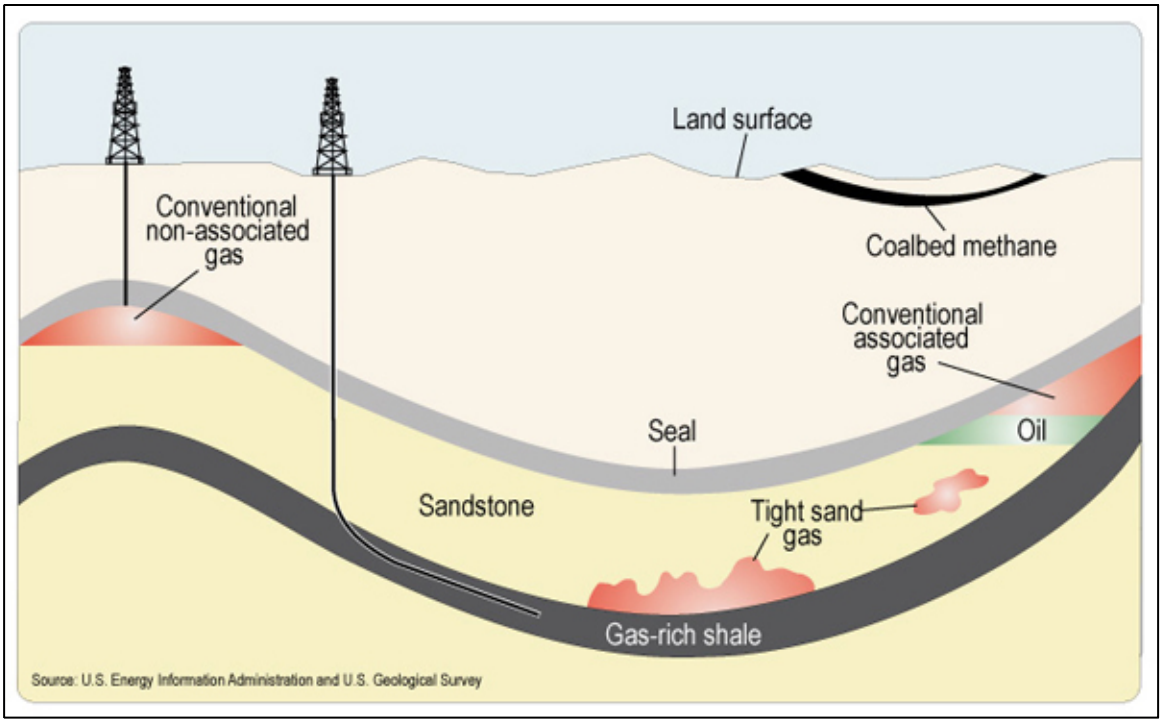


Figure 2.10. Drilling Types and Depth Relations for Fossil Fuel Extraction (USGS, 2002).

The process of extracting the gas starts with vertical drilling to the shale bed and then turning the drill horizontally for distances up to 3000 m (Kargbo et al., 2010). Perforations are created along the horizontal sections of the drill, and it is at these perforations where a highly pressurized water-based mixture is injected to fracture the shale and allow the trapped gases and liquids to flow back through the well.

The entire process of hydraulic fracturing is water intensive. According to Gregory et al. (2011), the process requires between about two and six million gallons of water, at each site, for drilling and fracturing. For example, in Pennsylvania well sites in the Marcellus Shale, drilling of one well lasts for an average of two to five days. During this period, the water required for fracking can range anywhere from three to five million gallons (New York State Water Research Institute, 2012). The drilling stage and fracturing processes directly impact local water supply (Gregory et al. 2011; Nicot and Scanlon, 2012) because of the amount of water needed at each well. If water is used in one sector, it cannot be used for another sector. The large water withdrawals associated with hydraulic fracturing can put a strain on the available water for other sectors.

After the water fractures the shale, the flowback stage begins. This is the process of the hydraulic fracturing fluid flowing back to the surface once pressure is relieved (Gregory et al., 2011, Kargbo et al., 2010; Montz et al., 2010). This flowback water is a mixture of natural gas and the water based fracturing compound, which contains brine, hydrocarbons, metals, acids, and radioactive elements (Montz et al., 2010). The total dissolved solids (TDS) in the flowback water can reach a concentration that is 5 times higher than seawater (Gregory et al., 2011), which has the potential to affect water supplies. If the flowback water mixes with either surface or groundwater supplies, it would make the water too toxic for human consumption or agricultural use before it is treated.

Hydraulic fracturing operations have been growing rapidly in the United States since 2007. Figure 2.11 shows the increase in natural gas withdrawals in the United States from 1,990,145 million cubic feet (mcf) in 2007 to 10,296, 572 mcf in 2012, a 417.4% increase in a five-year span. The growth of production in different shale beds has developed at different rates based on state drilling laws. Each state's experience with hydraulic fracturing differs from that of the United States as a whole (Table 2.2). Figure 2.12 shows the location of current and prospective shale plays, which are locations ripe for hydraulic fracturing.

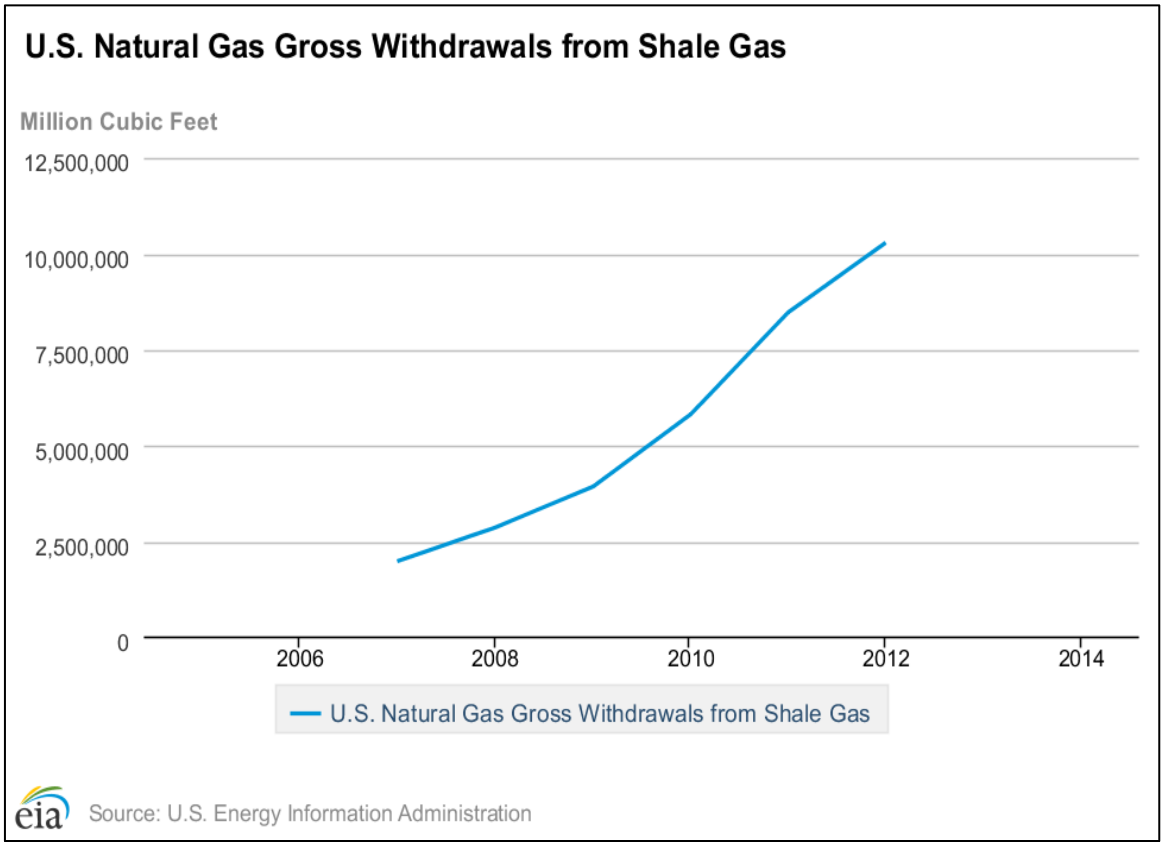
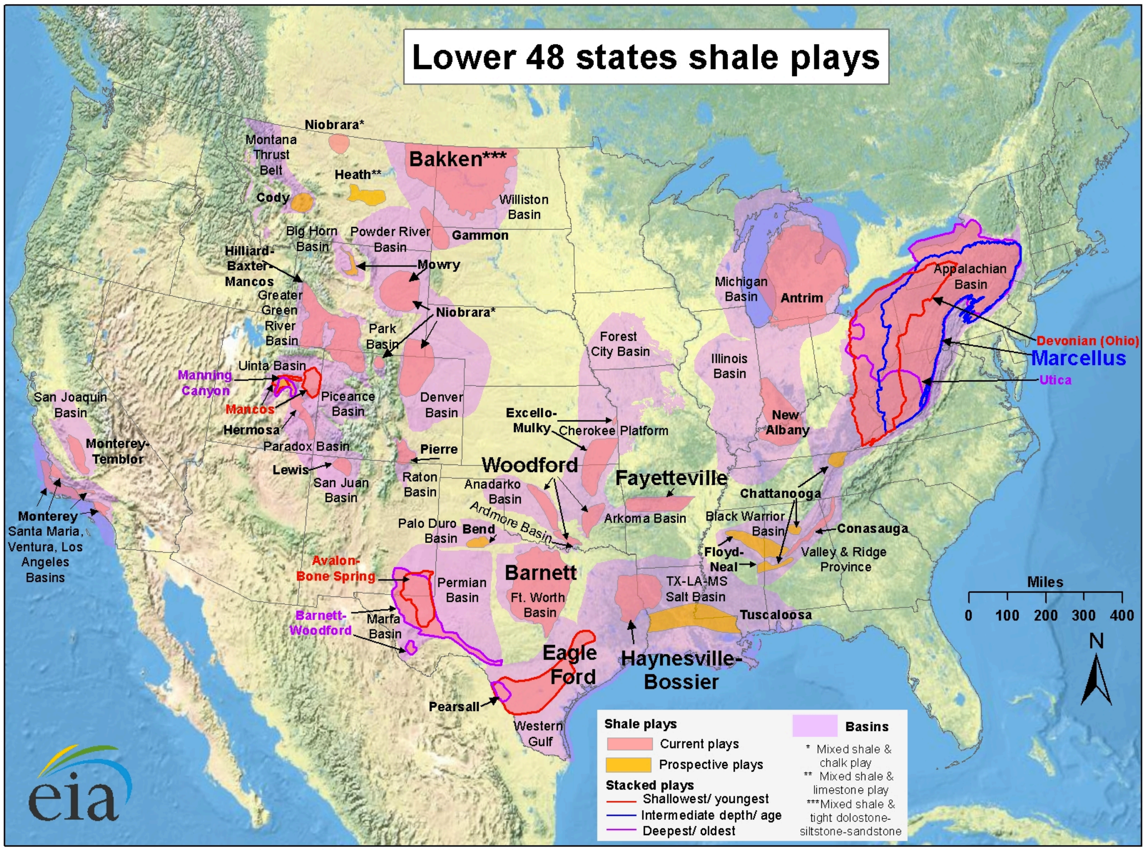


Figure 2.11. Natural Gas Production in MCF from 2008 to 2012 (US Energy Information (US EIA) Administration, 2014b).

Table 2.2. Shale Bed Natural Gas Production in the US and in Major Producing States from 2007 to 2012 (US EIA, 2014a).

Natural Gas Production from Shale Beds, 2007-2012 in mcf						
	Year					
Location	2007	2008	2009	2010	2011	2012
Total US	1,990,145	2,869,960	3,958,315	5,817,122	8,500,983	10,296,572
Texas	1,264,725	1,769,610	2,018,450	2,302,950	3,066,435	3,662,933
Pennsylvania	0	9,757	89,074	399,452	1,068,288	2,042,632
Colorado	138,335	164,334	180,310	195,131	211,488	228,796
Michigan	136,367	131,119	125,614	119,984	113,736	107,822
North Dakota	7,046	18,554	35,450	65,060	114,998	218,873



Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Figure 2.12. Current and Prospective Hydraulic Fracturing Practices in the US (US EIA, 2012).

As mentioned above, hydraulic fracturing is a water intensive industry. Therefore, the relationship between natural gas production rates and water use rates should be correlated. Table 2.3 shows the increase in the water use in the Susquehanna River Basin due to hydraulic fracturing in the Marcellus shale bed. From the third quarter of 2008 until the second quarter of 2012, there is a general increase in consumptive use of water used for hydraulic fracturing (Susquehanna River Basin Commission (SRBC), 2013). These data illustrate that the amounts of water consumed increase as hydraulic fracturing practices become more common and expand in the United States.

Table 2.3**.** Water Withdrawals for Fracking in the Susquehanna River Basin from 2008 to 2012. (SRBC 2013).

Quarter/Year	Period Ending	Total Consumptive water use (Mgal)	Average Daily Consumptive Rate by Quarter
Q3-2008	30-Sep-08	21	0.23
Q4-2008	31-Dec-08	35	0.38
Q1-2009	31-Mar-09	38	0.43
Q2-2009	30-Jun-09	76	0.83
Q3-2009	30-Sep-09	142	1.54
Q4-2009	31-Dec-09	222	2.41
Q1-2010	31-Mar-10	300	3.33
Q2-2010	30-Jun-10	543	5.97
Q3-2010	30-Sep-10	745	8.10
Q4-2010	31-Dec-10	716	7.78
Q1-2011	31-Mar-11	752	8.35
Q2-2011	30-Jun-11	906	9.95
Q3-2011	30-Sep-11	1,122	12.19
Q4-2011	31-Dec-11	1,035	11.25
Q1-2012	31-Mar-12	1,062	11.67
Q2-2012	30-Jun-12	1,101	12.10
Q3-2012	30-Sep-12	756	8.22
Q4-2012	31-Dec-12	715	7.77

Urban Water Management

The rapid growth of global populations since the Industrial Revolution has led to a shift in the locations of populations. Up until the mid 19th century, urban centers did not make up the majority of population. Since then, the process of urbanization has led to urban areas containing a vast majority of the world's population (Population Division, 2011). Due to urbanization in the 20th century, cities have been the largest consumers of water. With the current global population increase, the increase in industry, and looming uncertainties of climate change, the need for successful and sustainable water resources management is more important than ever.

The need for successfully meeting water demand has led to the increasing importance of water resources management. However, the management focuses have changed and evolved through time to more successfully meet water demands. The progression of management styles shifted from supply management to demand management for better protection of water supply (Novotny et al., 2010). Now, the focus is on integrated management with an emphasis on water resources sustainability. However, before these management styles are discussed, the properties of water quantity and water quality need be understood to get a deeper understanding of the evolution of water management styles.

Water quantity (amount of available water supply) is the founding principle in water resources management. Without an adequate quantity of water, a society cannot survive and large urban centers cannot exist. Water supplies are the ultimate product of the hydrologic cycle, and are usually found and used in the forms of surface waters (lakes and rivers) and ground waters (springs and aquifers) (Anisfeld, 2010). Areas that have large amounts of water are able to sustain large populations and are more resilient to pollution problems (water quality) than areas with less abundant water supplies.

The need for good water quality is essential because polluted water can carry constituents such as chemicals or microorganisms that can be harmful or that can cause disease. Water quality is dependent on the ratio of the contaminant(s) to the amount of water (USGS, 2014b). Each type of pollutant has a unique ratio to a volume of water for it to reach the polluted threshold. With that being said, greater water quantity means that there needs to be a higher quantity of a pollution to reach the polluted threshold. Managing polluted water is costly but very important due to the direct impact of water quality on public health (Kauffmann, 2011). The cost comes from the need for wastewater infrastructure to clean water to safe levels. Biswas and Tortajada

(2011) argue that future water crises will be the result of poor management of water resources and its impacts on water quality, not quantity. However, this has been more a of problem in less developed areas (Asia, Africa, and Latin America) where finances are less available to fund and build infrastructure to insure water quality (Biswas and Torajada, 2011).

Through time, both water quantity and water quality have been integrated into water resources management practices. However, water quality water quality has really only been a focus since the second half of the 19th century, where there has been a focus on water quantity since the first cities Before the Common Era (B.C.E.) (Novotny et al, 2010). Novotny explains five paradigms for water resources (Table 2.4). The first and the second focus on water quantity and the third and the fourth focus on water quality. These paradigms all focus on water supply. The fifth paradigm focuses on integrated water resources management (Novotny et al., 2010).

Table 2.4. Historical Types of Urban Water Management (Novotny et al., 2010).

Paradigm	Time Period	Characterization	Quality of Receiving Waters
1. Basic water supply	B.C. to Middle Ages; Can still be found in some developing countries	Wells and surface waters for water supply and washing; streets and street drainage for stormwater and wastewater.	Excellent in large rivers; in small and middle-sized streams, poor during large rains, good in between the rains.
2. Engineered water supply and runoff conveyance	Ancient Crete, Greece, and Rome; Cities in Europe in the Middle Ages until the Industrial Revolution in the 19th Century	Wells and long-distance aqueducts for public fountains, baths (Rome) and some castles and villas; some treatment of potable water; wide use of capturing rain in underground cisterns; some flushing toilets in public discharging into sewers, otherwise privies and outhouses.	Excellent to good in large rivers, poor to very poor in small and medium urban streams receiving polluted urban runoff contaminated with sewage; widespread epidemics from waterborne and other diseases.
3. Fast conveyance with no minimum treatment	From the second half of 19th century in Europe and U.S., later in Asian cities, until the second half of the 20th century in advanced countries, still persisting in many countries	Well and long-distance aqueducts for water supply; potable water mostly from surface sources treated by sedimentation and filtration; wide implementation of combined sewers in Europe and North America; initially no or only primary treatment for wastewater, secondary treatment installed in some larger cities after 1920s.	Poor to very poor in all rivers receiving large quantities of untreated or partially treated wastewater discharges from sewers, runoff discharged into sewers, and combined sewer overflow; rivers sometimes devoid of oxygen, with devastating effects on biota.
4. Fast conveyance with end of pipe treatment	From the passage of the Clean Water Act in the U.S. in 1972 to present	Gradual implementation of environmental constraints resulting in mandatory secondary treatment of biodegradable organics; regionalization of sewerage systems; additional mandatory nitrogen; recognition of nonpoint (diffuse) pollution as the major remaining problem; emphasis on nutrient removal from point and nonpoint sources.	Improved water quality in places where point sources pollution controls were installed; due to regionalization many urban streams lost their natural flow and became effluent dominated; major water quality problems shifted to the effects of sediment, nutrients, toxics, salt from de-icing compounds, and pathogens.

This paradigm focuses on sustainability and is sometimes referred to as “integrated resources management” (Novotny et al., 2010). Integrated resource management is centered on society, the environment, and the economy, how they relate to each other, and ultimately how they impact sustainability (Figure 2.13). Because rapid population growth and climate change are general concerns for future water resources, water management practices need to incorporate the relationship among social, economic, and environmental water needs and standards to achieve successful sustainability.

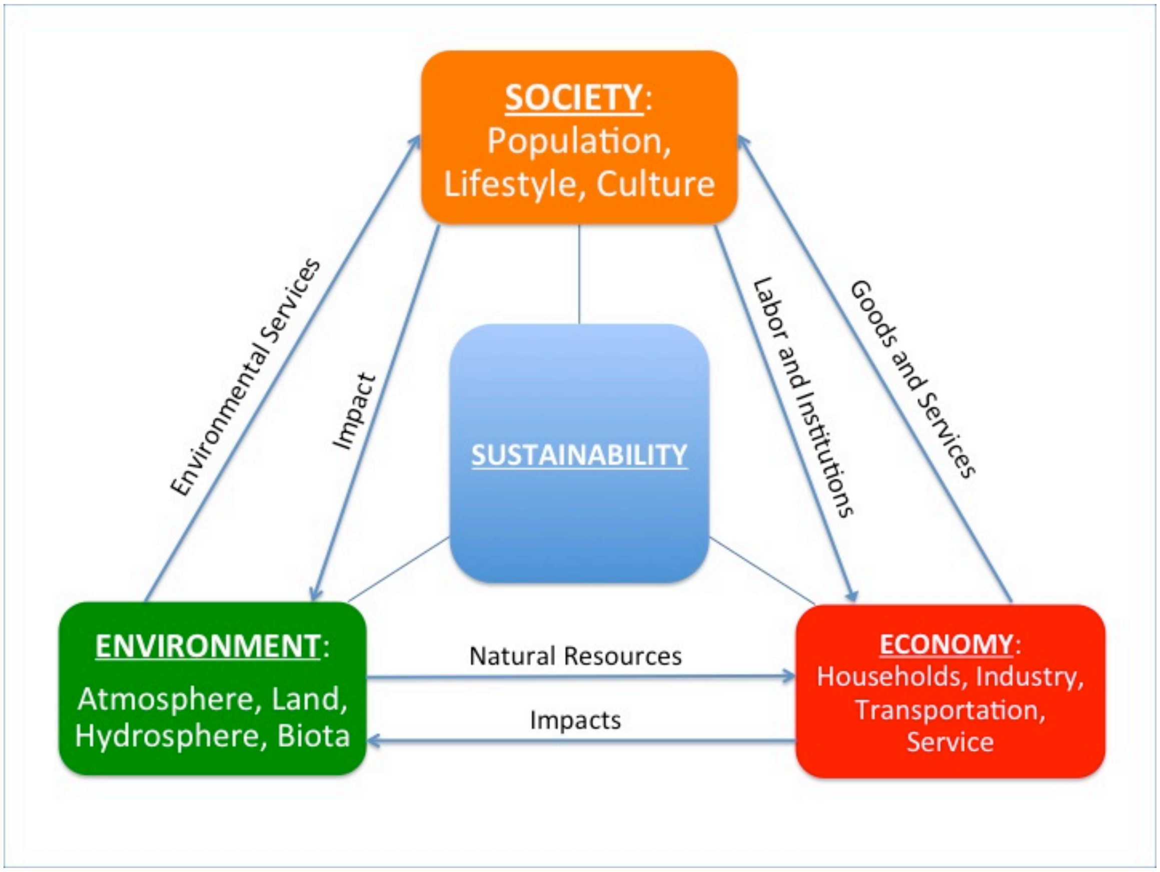


Figure 2.13. The Interdisciplinary Relationships for Integrated Resource Management (Novotny et al., 2010).

One component of integrated resources management is managing the demand for water. Demand management is seen as a more sustainable approach compared to supply management. Supply management focuses on meeting demands by bringing an adequate amount of water to an area, whereas demand management focuses on managing the amount of water that is needed versus the amount of water that is considered excessive (Brooks, 2006; Szesztay, 2009). According to Brooks (2006, p. 522), "In its simplest sense, water demand management means getting the most from the water we have." Essentially, demand management is the practice of using less water for a specific task, keeping water quality to the highest of standards, and improving knowledge of water use practice (Brooks, 2006). These in turn have a greater ability to meet water demands without the impacts of environmental degradation. Demand management is a crucial component of water management in urban areas because of the large water demands due to large population concentrations (Biswas, 2006). These large demands have the ability to cause extreme environmental degradation if withdrawals and wastewater are not managed (evident from the third paradigm discussed above).

Integrated resource management makes it possible to adequately meet demands in a sustainable way. Not only will integrated resource management practices, such as demand management, more effectively deal with current water issues in urban areas, but it has a better chance of mitigating future stressors (i.e. population growth, climate change, and higher industrial demands) because the management principle is focused on sustainability.

Even though the current outlook on water management styles and water use is becoming more of a focus, it does not mean that focus is uniform around the world. The places that currently suffer the most water problems are arid climates and developing countries (Varis et al., 2006; Pittock and Lankford, 2010). Much of the current literature focuses on water management in Asia because of both growing populations and rapid industrialization, which are inducing water stress (Varis et al., 2006; Biswas, 2008; Chen, 2001; Cosier and Shen, 2009).

This focus in the literature gives a skewed presentation of where actual water stress is currently occurring or where it could arise in the future. Due to rising populations, climate change, and growth in industrial demands, water stress will not be limited to arid regions and developing countries with poor water supplies or management practices. Regions like the

Southeastern United States are starting to feel dwindling water availability, despite the perception that the Southeast United States is “water rich” (Sun et al., 2008; Sohn, 2011). Furthermore, this region could feel the effects of an accelerated hydrologic cycle (discussed previously) and growing industrial water demands, both of which could exacerbate water stress. These issues will soon deconstruct the notion of regions being “water rich.” If more cities and regions successfully incorporate integrated resource management practices, these same locations may be considered “management rich” due to their ability to sustainably meet and manage water demand.

CHAPTER 3: THE STUDY AREA: RALEIGH-DURHAM, NORTH CAROLINA

The cities of Raleigh and Durham, North Carolina, part of Research Triangle Park, provide particularly useful locations to study urban water management and planning. The Triangle's population (the cities of Raleigh, Durham, and Chapel Hill and their surrounding suburbs) has been continually growing in large part due to the economic expansion of Research Triangle Park (RTP) (Figure 3.1). The Triangle, like the rest of the world, will have to face projected problems arising from climate change. In addition, North Carolina has recently legalized hydraulic fracturing, which as shown previously, requires large volumes of fresh water. The closest shale deposit to the Triangle is in Lee County, which is about forty miles south of Raleigh (Adair et al., 2012). These three factors could cause major changes in Raleigh's and Durham's available water supplies and could negatively affect the connectivity between these cities water supplies.

The water supplies for Durham and Raleigh are separate and not shared; however, their combined water supply sources are connected. Raleigh's primary source of water is Falls Lake, whereas the City of Durham obtains its water from Lake Michie, Little River Lake, and the Eno River (Figure 3.2 and 3.3). The city of Durham also has rights to 10% of the water contained in Jordan Lake. These systems are connected because Lake Michie, Little River Lake, and the Eno River flow into Falls Lake. Furthermore, the source of water for RTP is split between Durham County and Wake County. The Durham portion of RTP obtains its water from Lake Michie, and the Wake County portion of RTP obtains its water through the city of Cary, which is supplied by Jordan Lake (North Carolina Division of Water Resources (NC DWR), 2010).

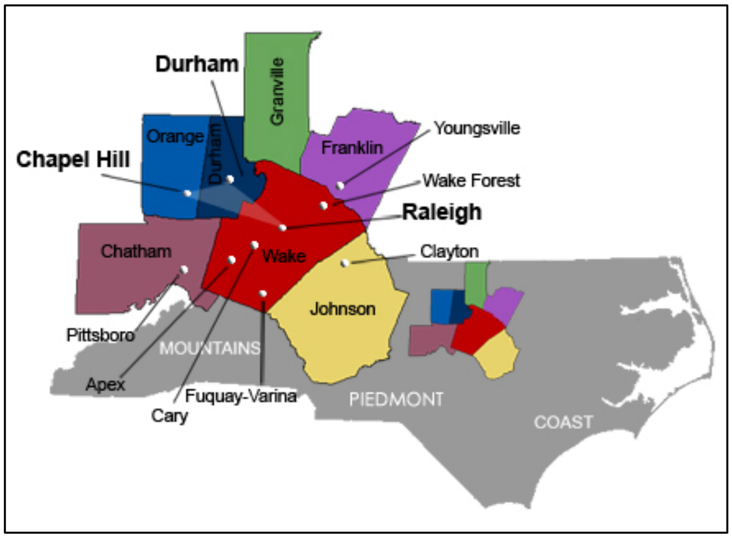


Figure 3.1. Research Triangle Park, North Carolina. (Triangle Home Showcase Realtors, 2014)

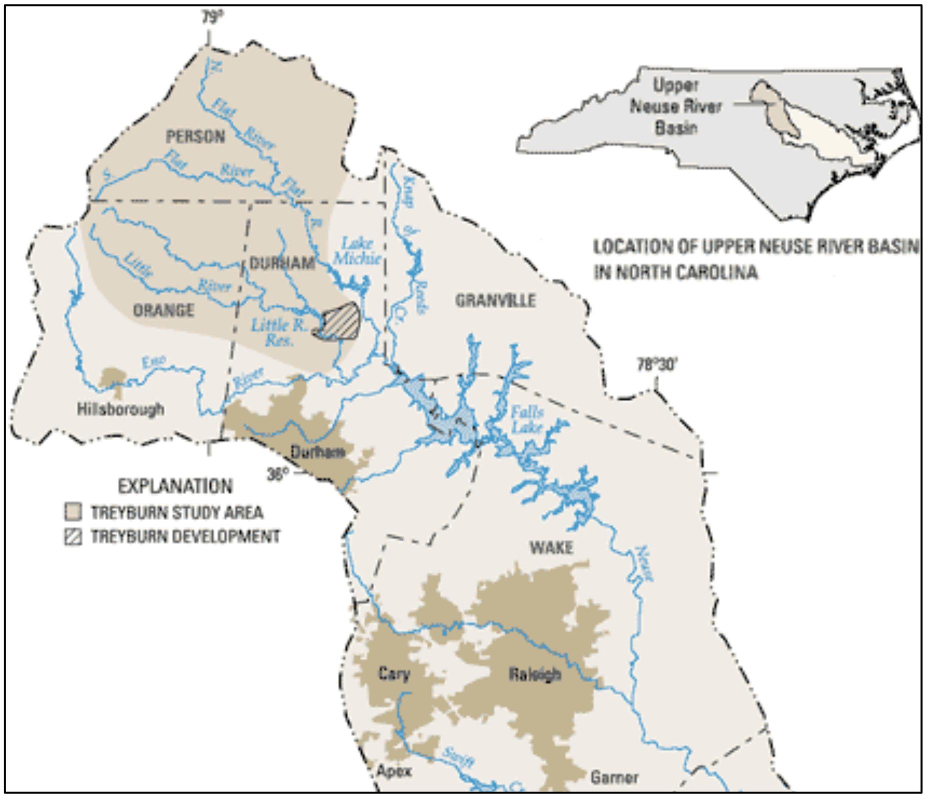


Figure 3.2. Lake Michie, Little River Lake, and Falls Lake in Relation to Raleigh and Durham, NC (USGS, 2014d).

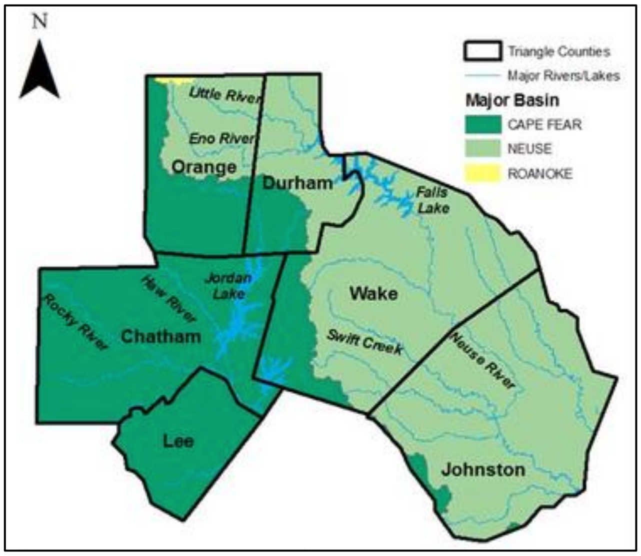


Figure 3.3. Falls Lake and Jordan Lake in Relation to Wake County and Durham County (Planners Web, 2014).

The Triangle area has been growing rapidly for the past two decades because of the job opportunities in RTP. Raleigh alone has seen major growth. *Forbes Magazine* ranked Raleigh as the second fastest growing city in America in 2011, the sixth fastest growing city in 2012, the fourth fastest growing city in America in 2013 and second fastest growing city in 2014.

NC DWR compiles water use data for each town in the state, in Local Water Supply Plans. These plans show how much water is available and how the water is being used. Furthermore, these data sets, which are updated annually, give projections on how demands and supplies could change in the future, including how population will change into the future. Table 3.1 compares the population projections from the 2008 data set and the 2013 data set for Raleigh, while Table 3.2 does the same for Durham. Comparison of these tables shows a significant increase in the projected rates of growth. In either scenario, significant population growth will impact water availability due to increased demand.

Table 3.1. NC DWR Population Projection Differences for Raleigh, up to 2050 (NC DWR, 2013b).

Raleigh, North Carolina			
NC DWR 2008			
Year	Population	Approx. % Increase	40 Year % Increase
2008	435,000	-	143.8%
2020	629,255	44.7%	
2030	765,125	21.6%	
2040	926,473	21.1%	
2050	1,060,472	14.5%	
Raleigh, North Carolina			
NC DWR 2013			
Year	Population	Approx. % Increase	50 Year % Increase
2013	489,000	-	150.7%
2020	683,300	39.7%	
2030	844,500	23.6%	
2040	995,700	17.9%	
2050	1,225,700	23.1%	

Table 3.2. NC DWR Population Projections Differences for Durham, up to 2050 (NC DWR, 2013a).

Durham, North Carolina			
NC DWR 2008			
Year	Population	Approx. % Increase	40 Year % Increase
2008	232,226	-	41.8%
2020	257,162	10.7%	
2030	288,271	12.1%	
2040	314,127	9.0%	
2050	329,280	4.8%	
Durham, North Carolina			
NC DWR 2013			
Year	Population	Approx. % Increase	50 Year % Increase
2013	262,725	-	58.1%
2020	286,419	9.0%	
2030	329,421	15.0%	
2040	372,423	13.1%	
2050	415,425	11.5%	

Neither Raleigh nor Durham has been free of the impacts of potential climate variability. The 2007-2008, "drought in North Carolina was the worst in the 112-year recorded rainfall history" (NCDWR, 2009, p. 11). The drought covered most of the state, such that water restrictions affected 5 million people and 53 percent of North Carolina's public water systems. Thirty cities rationed water, and some cities' water dipped to 100 days' supply. There was a total of 7,200 wildfires, which is well above the average of 5,000 annual wildfires in North Carolina, and agricultural damages were estimated at 500 million dollars in destroyed crops (NC DWR, 2009). The drought affected North Carolina's local water supplies, including the water supplies for the cities of Raleigh and Durham.

Climate change is not the only impact on water availability; it is also dependent on demand, as discussed earlier. Population growth does not just affect domestic water demands, it also causes industrial water demands to increase, especially if new industries come to the region. North Carolina legalized hydraulic fracturing in 2012 because of the industry's potential to increase North Carolina's economy. In 2012, North Carolina Department of Environment and Natural Resources (NC DENR) and the North Carolina Department of Commerce (NC DOC) undertook a study on all aspects of hydraulic fracturing and its applications in North Carolina. This report covered issues ranging from environmental to economic impacts. From an economic standpoint, this report estimates that hydraulic fracturing could increase economic output by 453 million dollars, when drilling operations are fully completed in North Carolina (NC DENR, 2012).

As of May 2014, the North Carolina Government had been working on putting hydraulic fracturing on the "fast-track," meaning that the NC government has been taking measures to encourage hydraulic fracturing in this state in the near future. Right now, only land leases have been allowed, but these leases could turn into permits, by law, as early as spring of 2015 (Henderson, 2014). Currently, under law, it illegal for local governments in North Carolina to ban fracking, which shows that the North Carolina State government is pushing hard for hydraulic fracturing to come to the state in the near future (Henderson, 2014).

The shale beds in North Carolina are relatively small, but as of 2014 the push for hydraulic fracturing has already started. According to Reid et al. (2011), there are two Triassic shale beds that are located in North Carolina: the Deep River basin and the Dan River basin. The shale bed most relevant to the Raleigh-Durham area is the Deep River basin, where the specific sub basins are the Sanford sub-basin and the Durham sub-basin (Figure 3.4). The Sanford sub-basin covers an area of 146,530 acres, whereas the Durham sub-basin covers an area of 405,236 acres. However, the total area will not be fracked. Property owners on the land above the shale deposits have to lease their land to the oil and gas companies to allow drilling to take place.

Due to hydraulic fracturing's water intensive needs, interbasin water transfers may be required to meet the large water demands. The reservoirs that Raleigh and Durham use to support their populations are the closest large bodies of water to Sanford, which makes them particularly suitable sources of water. However, if this does not occur, incorporating hydraulic fracturing in this study presents a worst-case scenario for evaluating increases in industrial uses. In one scenario (the one used in this research), Raleigh's and Durham's water supplies could be tapped to supply water for hydraulic fracturing, placing additional, and potentially unanticipated, stress on their water supply systems.

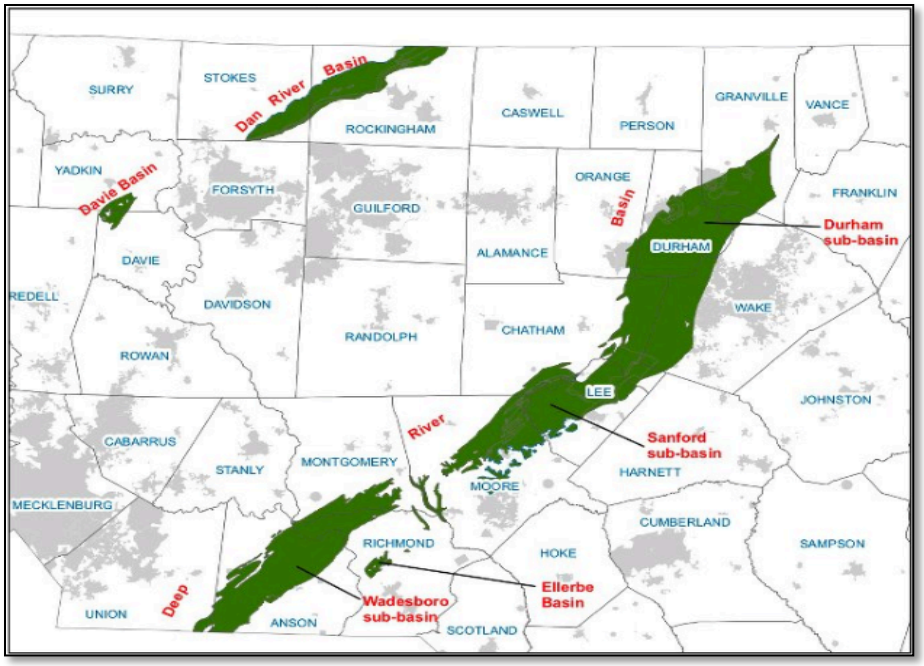


Figure 3.4. Shale Deposits in North Carolina.

In Wake County, where Raleigh is located, the largest users are public water supply at 53 mgd and thermal electric power at 37 mgd (Figure 3.5) (NC DWR, 2013b). The demands for Wake County are similar but different to Raleigh's major demands. The major uses in Raleigh are public supply at 20 mgd, commercial at 16.4 mgd, and industrial at 2 mgd (NC DWR, 2012b). These numbers are only projected to increase into the future due to the growth discussed earlier.

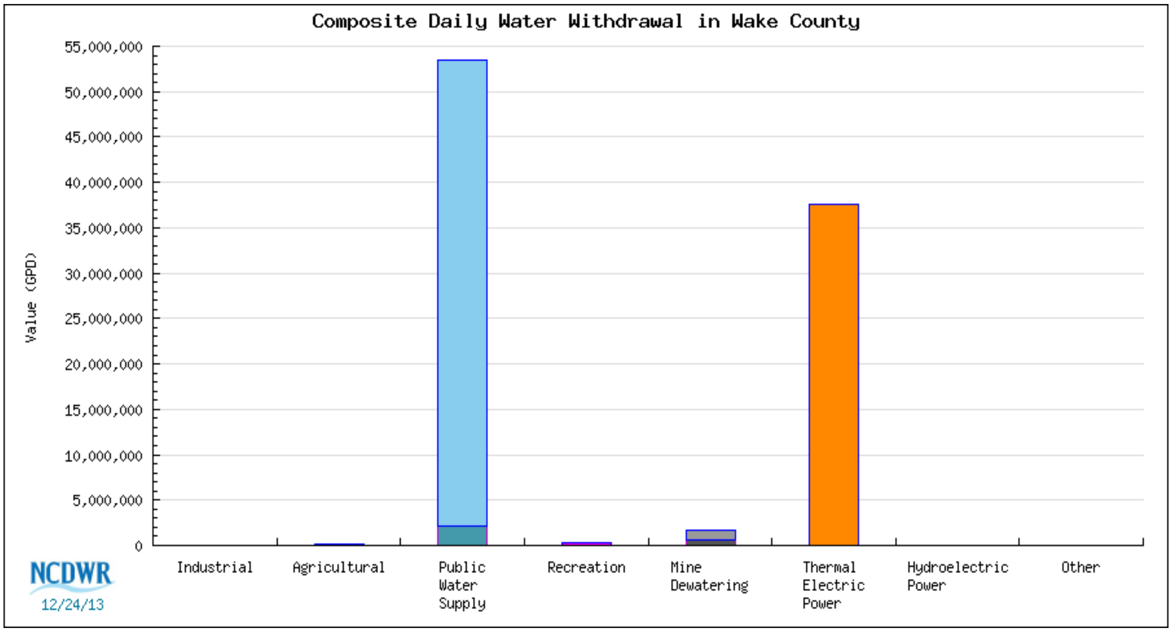


Figure 3.5. Total Water Demands for Wake County (NC DWR, 2012b).

Water demands in Durham County and the City of Durham vary from each other, the city of Raleigh, Wake County, and the State of North Carolina. Durham County only has one major water sector, which is public supply at 37 mgd (Figure 3.6) (NC DWR, 2013a). The City of Durham's major water users are public supply at 11.4 mgd, commercial at 6.6 mgd, institutional at 3.3 mgd, and industrial at 1.3 mgd (NC DWR, 2012a). Like Raleigh, these demands will increase in the future with population growth.

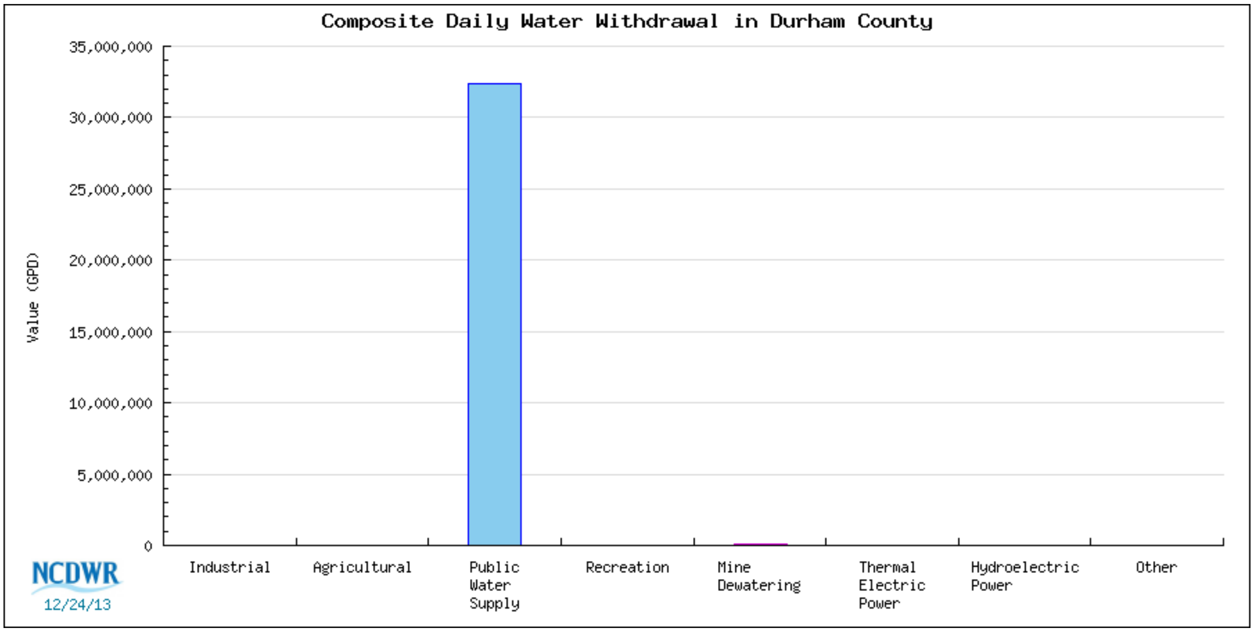


Figure 3.6. Total Water Demands for Durham County (NC DWR, 2012a).

Both Raleigh and Durham published reports in 2010 and 2009, respectively (City of Raleigh, 2010; City of Durham, 2009), which define the steps each will take during times of water shortages. These plans were drafted after the drought of 2007-2008, and are designed to only be implemented when water supplies are stressed. Both the City of Raleigh and the City of Durham have comprehensive plans, which account for population growth; however, neither comprehensive plan accounts for climate change nor increases in industrial water demand (City of Raleigh, 2011; City of Durham, 2012).

These Water Shortage Response Plans (WSRPs) provide the steps that will be taken when water shortages occur. However, they do not account for variations when shortages in supplies usually occur, or when water demands are higher than the annual mean. This presents a problem because precipitation patterns, stream flow, water availability, and water demands are not constant all year round. Stream flow from Falls Lake varies during the year. In the fall and winter seasons as defined by NC DENR (months of November to March), stream flow averages between 40-65 cubic feet per second (cfs), while in the spring and summer seasons (months of

April to September) stream flow averages 100 cfs (Table 3.3). Furthermore, water demands vary seasonally. Figure 3.7 shows the average monthly demands over a 10-year span. It is evident that water demands are higher in the summer months and lower in the winter months. However, due to greater water availability in the summer season, the higher summer demands are not as taxing on the water supply.

Table 3.3. Seasonal Variation in Stream flow out of Falls Lake (NC DWR, 2010)

Months of the Year	**Immediately Below Dam**	**USGS Gage at Clayton**
November- March	40-65 cfs, 26-42 mgd	184 cfs, 119 mgd
April- October	100 cfs, 65 mgd	254 cfs, 164 mgd

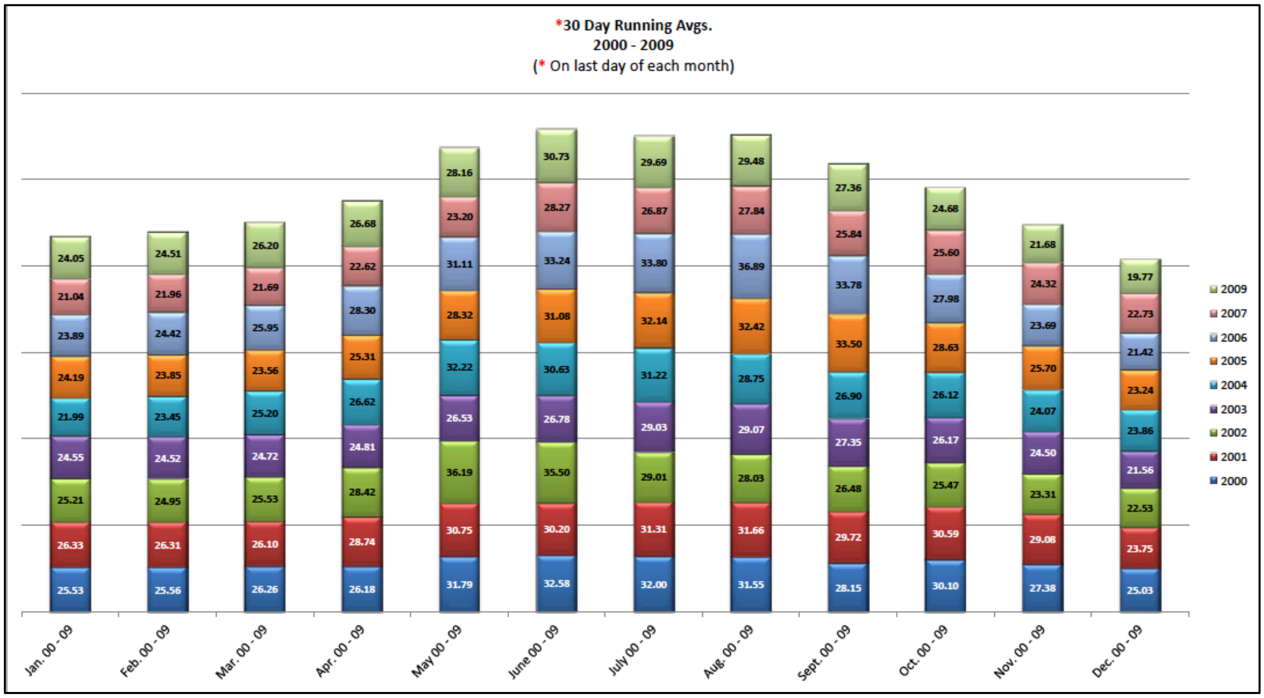


Figure 3.7. Monthly Water Demand Changes in Durham from 2000 to 2009.

Adding the water supply needs of hydraulic fracturing may induce water supply shortages in seasonal time frames simply because demand may be greater than supply at least over short time horizons. Table 3.4 shows not only the increasing rate of water consumption in the Marcellus shale within the jurisdiction of the Susquehanna River Basin Commission (SRBC), but also the variation of water use throughout the year. According to Nicot and Scanlon (2012), hydraulic fracturing has the greatest impact on water supplies at the local level. Localized, seasonal shortages appear to be a concern among local populations in the Marcellus Shale region of Pennsylvania and New York (US Environmental Protection Agency, 2011).

Table 3.4. Water Withdrawals for Fracking in the SRB from 2008-2012 (SRBC, 2013)

Quarter/Year	Period Ending	Total Consumptive water use (Mgal)	Average Daily Consumptive Rate by Quarter
Q3-2008	30-Sep-08	21	0.23
Q4-2008	31-Dec-08	35	0.38
Q1-2009	31-Mar-09	38	0.43
Q2-2009	30-Jun-09	76	0.83
Q3-2009	30-Sep-09	142	1.54
Q4-2009	31-Dec-09	222	2.41
Q1-2010	31-Mar-10	300	3.33
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Q4-2011	31-Dec-11	1,035	11.25
Q1-2012	31-Mar-12	1,062	11.67
Q2-2012	30-Jun-12	1,101	12.10
Q3-2012	30-Sep-12	756	8.22
Q4-2012	31-Dec-12	715	7.77

When looking at population growth and industrial water demand changes and their effects on water supply, it is already difficult to project what implications these will have on Raleigh's and Durham's water supplies. If climate change is added into the equation, expected water recharge is likely to be limited. If recharge is limited, then Raleigh's and Durham's water supplies may not be adequate to meet demands of population growth or industrial water demand changes or both.

Raleigh’s and Durham’s existing water management plans account for anticipated population growth but do not account for other potential stressors on water supply, including climate change and increased industrial water demands from hydraulic fracturing or other industries. A more informed water management plan would account for these two factors. Climate change and population growth may interact such that water supply does not meet demand over some time horizons. Furthermore, hydraulic fracturing may further exacerbate water supply stress by adding additional water demands.

CHAPTER 4: METHODS AND ANALYSIS

This chapter provides a detailed description of the methodological and analytical approaches used in this research. Due to the complexity associated with evaluation of how each factor could affect water supply, many different types of data were needed, along with multiple equations to evaluate impacts to water supply. This chapter is divided into five parts: 1. data collection, 2. water demand analysis, 3. climate change analysis, 4. hydraulic fracturing analysis, and 5. multi-factor analysis. Before any analysis can be discussed, the methods of data collection need to be outlined and examined.

Data Collection

Three categorical types of data were needed: water demand data, climate data, and hydraulic fracturing data. Each of these has multiple subsets of data, which were used to fully analyze the impacts of each factor on water supply in the most effective way. These different analyses are shown in Figure 4.1.

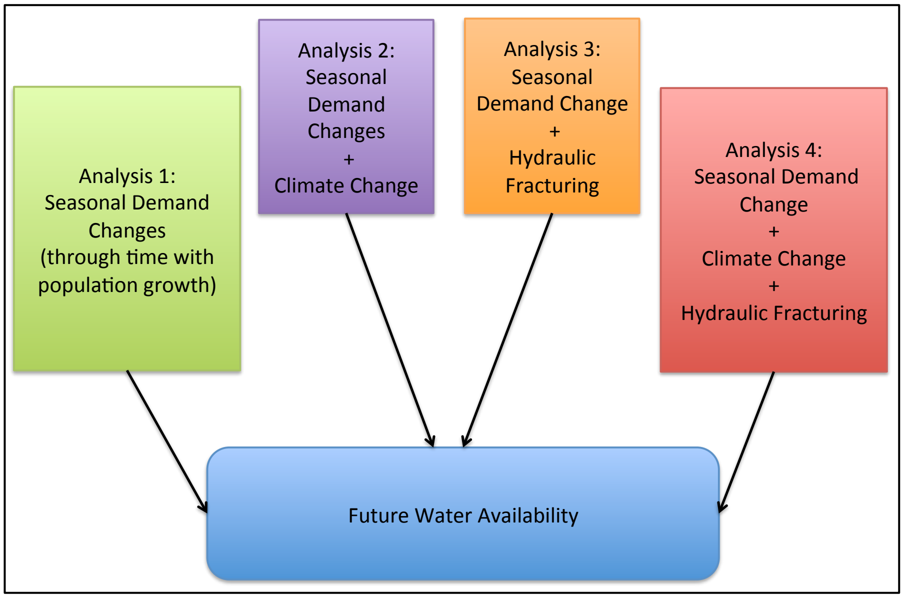


Figure 4.1**.** Four Analyses of this Research and the Different Impacts to Water Availability.

Population and Water Demand Data

The NC DWR, under NC DENR, makes available water data for every city in North Carolina, in the Local Water Supply Plans (LWSPs). These data sets are updated every year with current conditions and future projections of many types of water data. These data sets contain population figures, annual water demand (which is broken down by sector), and annual available supply, based on current conditions and projected for the next five decades. Furthermore, the percentage of demand versus supply is given for each year's projection. This allows one to easily see if or when demand is projected to outstrip supply.

Unfortunately, these annual projections do not evaluate seasonal variability. This is important because water demands and supply do not stay constant throughout the year. The LWSPs provide monthly demand data for each projection, which was used to find seasonal averages. This is described in the section on domestic water demand analysis.

Climate Data

The climate data needed for this research was obtained from a number of sources. The IPCC's Assessment Report number 4 (AR4) from 2007 was used for the climate change projections. These projections provide forecast changes in precipitation and temperature from current conditions; however, current conditions are not provided in AR4. As a result, current precipitation and temperature data were obtained from the Southeast Regional Climate Center (SERCC). The SERCC has historical data from every weather station under its jurisdiction, three of which are most relevant to Raleigh and Durham: Durham (weather station 312515), Raleigh-Durham airport (RDU) (weather station 317069), and Raleigh at NC State University (weather station 317079) (SERCC 2014a, b, and c). From these three weather stations, it was possible to collect historical monthly averages for both precipitation and temperature. However, these data sets do not provide historical average wind speeds or dew point temperatures for each month. Therefore, these data were collected from the State Climate Office of North Carolina (2014) from the RDU weather station (317069). The data were not available for the other two weather stations, so the data from RDU was used for all three.

Wind speed and dew points are needed to calculate water evaporation from large bodies of water. The other data needed for this is water temperature, stream gauge height and surface area of each lake (Falls Lake, Lake Michie, Little River Lake, and Jordan Lake) which were obtained from the USGS (2014c).

Hydraulic Fracturing Data

Because Pennsylvania has had significant growth in hydraulic fracturing and natural gas extraction, most of the North Carolina projections of fracking are modeled after Pennsylvania. Annual reports from the Bureau of Oil and Gas Management of the Pennsylvania Department of the Environment (PA DEP), from 2009-2012 (four total), modeled how many land leases were converted into actual drilling operations, and the results of these models are used here. Similarly, a report by Manda et al. (2014), studied the effects of hydraulic fracturing's water footprint in the Marcellus Shale, which served as the data on how hydraulic fracturing operations change through time.

Although data from Pennsylvania and the Marcellus Shale provide models for how hydraulic fracturing might take place and change through time in North Carolina, it does not give baseline conditions for how hydraulic fracturing may take place in another location, which is needed in order to apply the Marcellus projections. Baseline conditions were derived from different sources in North Carolina.

NC DENR and NC DOC's hydraulic fracturing report in 2012 was used in part for hydraulic fracturing scenarios relating to well density and how much water could be used for each well, described later. However, the extent of shale beds in North Carolina was needed for calculating baseline conditions, which was obtained from Reid et al. (2011). The Lee County Government has a data set showing how much land in Lee County is already leased to gas companies for drilling, which was used for determining baseline conditions for North Carolina.

Once the data for each component was collected, each was then analyzed, in the same order as the data was collected. The following sections give the detailed steps of analysis for each component of this research.

Water Demand Analysis

Domestic Water Demand Analysis

Population growth projections from 2020 to 2050 for both Raleigh and Durham are significantly different between the 2008 and the 2013 reports. Therefore the future population projections will serve as two different scenarios of demand (Table 4.1). The 2008 report projects up until 2050, whereas the 2013 report projects until 2060 because each report shows data for the then current year and then projects for the start of the next five decades (e.g. 2020, 2030, 2040, etc.). However, in this research, the 2013 LWSP projections to 2050 will be used. This way the future time frame will be the same for both the 2008 and 2013 LWSP projections. This population data was used instead of data from the US Census Bureau because of the direct links to water use for each municipality.

Table 4.1. Difference in LWSP Population Projections in 2008 Report and 2013 Report (NC DWR 2013a; 2013b).

	Raleigh, North Carolina		Durham, North Carolina	
Year	NC DWR 2008	NC DWR 2013	NC DWR 2008	NC DWR 2013
2008	435,000	-	232,226	-
2012	-	489,000	-	262,725
2020	629,255	683,300	257,162	286,419
2030	765,125	844,500	288,271	329,421
2040	926,473	995,700	314,127	372,423
2050	1,060,472	1,225,700	329,280	415,425

The LWSPs project increased rates of water demands by different sectors in relation to the projected population growth (see Table 4.2 for the example of Raleigh). These demand values and projections are given in millions of gallons per day (mgd). The reports show the water demands for each sector and the percentage of total demand compared to available supply; however, these projections only provide the annual mean values of demand for each sector. Therefore, seasonal demands must be calculated to evaluate the variation from the annual average.

Table 4.2. Water Demands By Sector, Total Demand, Available Supply for the City of Raleigh (NC DWR, 2013b).

RALEIGH						
	2013	**2020**	**2030**	**2040**	**2050**	**2060**
Year-Round Population	489,000	683,300	844,500	995,700	1,225,700	1,508,800
Seasonal Population	0	0	0	0	0	0
Residential	19.99	39.56	46.63	52.23	58.12	65.08
Commercial	16.42	15.36	18.1	20.28	22.56	25.26
Industrial	2	1.75	2.06	2.31	2.57	2.88
Institutional	3.28	4.57	5.39	6.04	6.72	7.52
System Process	0.1	3.07	3.63	4.06	4.46	5.06
Unaccounted-for	6.706	5.59	6.59	7.38	8.22	9.2
Sales	0.001	0.41	0.41	0.41	0.41	0.41
Total Demand (MGD)	48.497	70.31	82.81	92.71	103.06	115.41
Total Available Supply (MGD)	78.2	78.2	91.3	91.3	91.3	91.3
Demand as Percent of Supply	62%	90%	91%	102%	113%	126%

Data were analyzed in multiple steps to determine the changes in water demand on a monthly basis. The LWSPs give the monthly water demands for the current year, but monthly demand varies from year to year. Therefore, to obtain an average water demand for each month, the annual reports for each month from 2006 to 2013 were averaged together. This time frame was used because there are only annual LWSP reports from the years 1997, 2002, and 2006 to 2013, so the most current averages were calculated. After the average monthly demand totals were calculated, they were averaged with the other months for each corresponding season to calculate seasonal variability. The four seasons are broken down as such: Spring (March, April, May), Summer (June, July, August), Autumn (September, October, November), and Winter (December, January, February). These seasonal averages were used to calculate seasonal variability in demand into the future.

Climate Change Analysis

Due to the complexity associated with predicting how climate could change in the future, let alone its impacts on water availability, multiple calculations and processes based on a range of climate data are required. Given the timing of this research, projections from IPCC's Assessment Report (AR4) (2007) are used in this research.

AR4 gives ranges for both temperature and precipitation changes in the future, both of which are important to water supply. Figure 4.2 maps the progression of the methodology used here to evaluate the impacts of climate change and other factors on water availability. Precipitation variations will change how much water is being delivered to the reservoir systems, whereas temperature changes will cause evaporation rates to increase. The higher the air temperatures, the higher the capacity for evaporation of surface waters. From the data in AR4, three scenarios (best, mean, and worst case) were derived. The best-case scenario combines minimum temperature increases with a maximum precipitation increase, which allows for greater precipitation input to the reservoir systems with less evaporation due to smaller increases in air temperatures. The mean-case scenario combines the mean projections for both precipitation and temperature changes. The worst-case scenario combines higher temperature increases with lower precipitation values, which would cause less water to be delivered to the reservoir areas and higher evaporation rates, leading to less water availability. Table 4.3 shows the different scenarios of precipitation and temperature change projections from current conditions in the form of seasonal variability, where precipitation ranges from increased amounts to decreased amounts and temperature changes are all increased from current conditions.

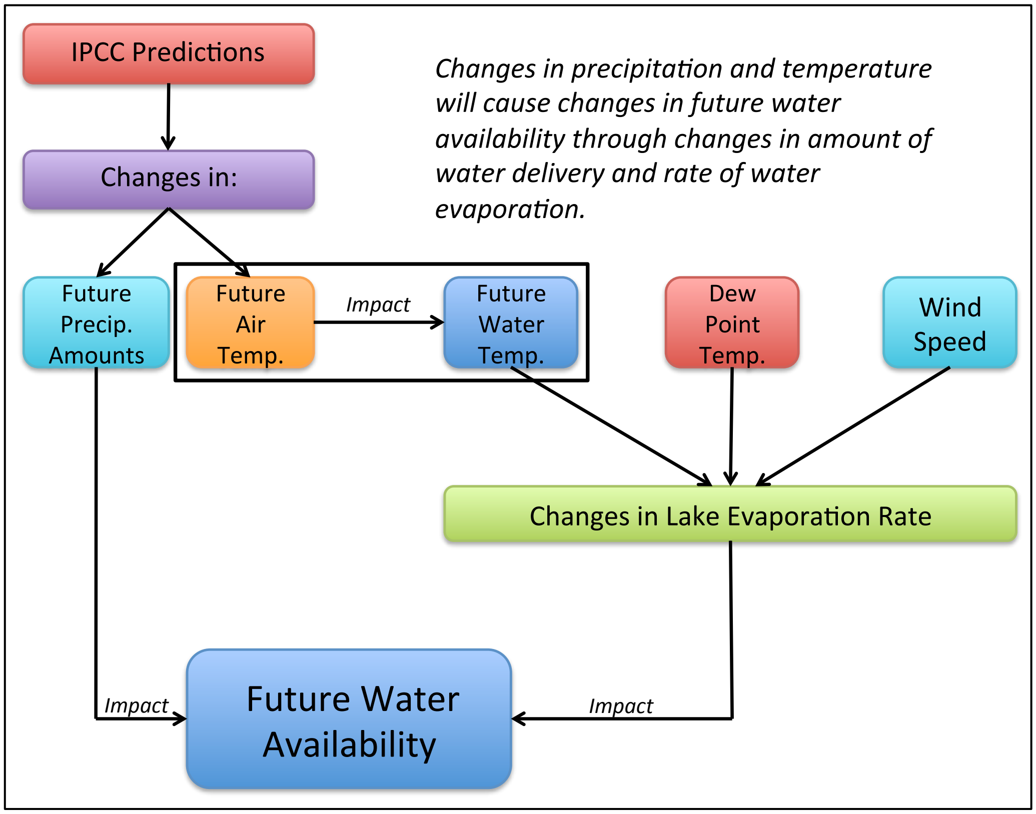


Figure 4.2. The Components of this Research's Methodology and how Climate Change will Impact Water Availability in the Future.

Table 4.3. Scenarios of AR4 Projections on Seasonal Temperature and Precipitation Variability (IPCC, 2007).

Climate Change Scenarios (IPCC AR4)						
Season	Scenarios					
	Best Case		Mean Case		Worst Case	
	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
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
Autumn	17%	2.2°C	7%	3.5°C	-7%	5.7°C
Winter	28%	2.1°C	11%	3.8°C	2%	6.0°C

IPCC projections encompass regions, which are large and have current precipitation and temperature variations within them. For example, North Carolina and Pennsylvania are within the same IPCC region (the eastern United States), so AR4 predicts the same precipitation and temperature variations in the future. However, North Carolina and Pennsylvania have different current base conditions for precipitation and temperature due to their locational differences. Therefore, the impacts of future climate change will be different in each of these states when the projections are applied to current conditions. This same method of analyzing future climate change projections was used by Griffin et al. (2013), which proved effective.

Because of regional differences, not just between different states but also between different regions within a state, base conditions are needed from local areas to determine the most reasonable climate change impacts in an area. Because the study site in this research is Raleigh and Durham, North Carolina, current conditions are based on climatic data from weather stations in the area.

Precipitation and temperature data for the three weather stations used in this research were obtained from the Southeast Regional Climate Center (SERCC), which provides historical monthly averages for precipitation and temperature (Table 4.4). The historical data provided is already averaged by month, so it was not possible to obtain the same length of record from each station.

Table 4.4. Weather Station Identifications and Reporting Ranges (SERCC, 2014a, b, c).

Weather Stations		
Location	Station ID	Historical Reporting Range
Durham	312515	1899-2012
Raleigh-Durham	317069	1948-2012
Raleigh	317079	1921-2012

The SERCC historical weather station reports provide maximum, minimum, and mean values for each month for both precipitation and temperature. Only the mean was used for both precipitation and temperature because the maximum and minimum incorporate extreme ranges that do not happen regularly. The mean values represent average or normal conditions and the aim of this research is to evaluate how normal conditions could vary in the future with climate change. Tables 4.5 and 4.6 show the average precipitation and temperature, respectively, for each weather station.

Table 4.5. Mean Monthly Precipitation Values for Each Weather Station (SERCC, 2014a, b, c).

Monthly Precipitation averages in Inches			
Month	Durham	Raleigh-Durham	Raleigh
January	3.55	3.44	3.58
February	3.41	3.26	3.43
March	4.05	3.85	3.98
April	3.37	2.88	3.11
May	3.74	3.54	3.82
June	4.2	3.57	4.13
July	4.62	4.59	4.81
August	4.53	4.45	4.61
September	3.61	3.89	4.23
October	3.09	2.99	3.15
November	3.02	3.05	3.08
December	3.26	3.09	3.33

Table 4.6. Mean Monthly Temperature Values for Each Weather Station (SERCC, 2014a, b, c).

Average Temperature (°C)			
	Durham	Raleigh-Durham	Raleigh
January	4.333	4.667	5.167
February	5.500	6.111	6.389
March	9.667	10.222	10.611
April	14.889	15.333	15.611
May	19.500	19.667	20.056
June	23.778	23.889	24.222
July	25.611	25.944	26.111
August	24.944	25.278	25.333
September	21.667	21.722	22.278
October	15.444	15.667	16.167
November	9.833	10.500	11.111
December	5.389	5.833	6.278

The monthly data were converted into seasonal values as follows: the precipitation totals for each month in each season were added together and the temperature values for each month were averaged with the other months in each respective season. For example, to find the average precipitation for winter, the values for December, January, and February were summed. For average winter temperature, the values of December, January, and February were averaged (Table 4.8). These procedures provide the base or current values for precipitation and temperature in the area. Table 4.9 presents the current conditions applied to the three scenarios to show how precipitation amounts and temperature values could vary in the future.

Table 4.7. Average Monthly Precipitation and Temperature around Raleigh and Durham, NC (SERCC, 2014a, b, c).

Average Monthly Values based on 3 Weather Stations		
Month	Precipitation (in.)	Temperature (°C)
January	3.523	4.722
February	3.367	6.000
March	3.960	10.167
April	3.120	15.278
May	3.700	19.741
June	3.967	23.963
July	4.673	25.889
August	4.530	25.185
September	3.910	21.889
October	3.077	15.759
November	3.050	10.481
December	3.227	5.833

Table 4.8. Average Seasonal Precipitation and Temperature Values around Raleigh and Durham, NC (SERCC, 2014a, b, c).

Seasonal Average of Current Precipitation and Temperature		
Season	Precipitation (in.)	Temperature (°C)
Spring	10.780	15.062
Summer	13.170	18.759
Autumn	10.037	12.032
Winter	10.117	5.519

Table 4.9. IPCC Precipitation and Temperature Scenarios Compared to Current Conditions.

Scenarios for Precipitation and Temperature Change from Current Conditions								
	Current Conditions		Best-Case		Mean-Case		Worst-Case	
Season	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
Spring	10.78 in	15.06 °C	13.26 in	17.36 °C	12.07 in	18.56 °C	10.35 in	20.96 °C
Summer	13.17 in	18.76 °C	14.88 in	20.76 °C	13.30 in	22.06 °C	10.93 in	24.17 °C
Autumn	10.04 in	12.03 °C	11.74 in	14.23 °C	10.74 in	15.53 °C	9.33 in	17.73 °C
Winter	10.12 in	5.52 °C	12.95 in	6.519 °C	11.22 in	9.32 °C	10.32 in	12.89 °C

Following this, the next step is to evaluate how changes in precipitation and temperature might impact water availability. A simple water balance equation is used to model future changes in water availability. The equation for a water balance is $S = P + G_{in} - (Q + ET + G_{out})$, where change in storage equals precipitation (P) plus ground-water inflow (G_{in}) minus (stream outflow (Q) plus evapotranspiration (ET) plus ground-water outflow (G_{out})) (Dingman, 2002). Because this research only focuses on surface waters, ground water inflow and outflow are ignored. Along with groundwater, because these water supply systems are reservoirs, stream outflow was also not considered. It should be noted that the groundwater component is important when considering water supplies. However, according to the LWSPs, both Raleigh and Durham meet all their water demands with surface water supplies, which means that the cities do not directly take groundwater for public need. Therefore, this research only evaluates future fluctuations in surface water supplies. Similarly, because the water supply systems that this research addresses are reservoir systems, evapotranspiration was not evaluated. Instead only water evaporation was evaluated. Therefore, the formula specifically used here is $\Delta S = P - E$ (change in storage equals precipitation minus evaporation).

To calculate a change in storage from current conditions to future conditions, multiple steps were used. The first was to evaluate each season’s current storage amount. This was calculated, first, by setting the current seasonal conditions to current data, using each reservoir's historical monthly gauge heights. The average monthly value for each month in a season was averaged (as done with precipitation and temperature data above) (USGS, 2013). The seasonal average gauge heights served as the current storage capacity for each season. Current precipitation data was used for the current "P" value in the equation.

Modeling current evaporation conditions was a more involved process. To calculate evaporation for the equation above, multiple steps were taken. The formula for open water evaporation is $E = C\ (e_0 - e_a)(1 + \frac{W}{10})$, where C (0.36) is the pan empirical (evaporation) coefficient for daily data on an ordinary lake, e_0 is the saturation pressure of the water temperature, e_a is the actual vapor pressure of the air, and W is wind speed (Viessmann and Lewis, 1996). Saturation pressure is derived from the temperature of the water, which was retrieved from the USGS, which provides average monthly temperatures (USGS, 2014c). These were converted into seasonal averages. To find the saturation pressure of the water, average seasonal temperature data were converted from degrees Celsius to Kelvin for input to the equation for saturation pressure, $e_0 = 6.11 \times 10^{\frac{(7.5 \times T)}{(237.3+T)}}$ (Petty, 2004). Here T stands for air temperature. The calculated saturation pressure is measured in inches of Mercury (in. of Hg).

To solve for actual vapor pressure, dew point temperatures are needed. Monthly average dew point temperatures were acquired from the North Carolina State Climate Office for the Raleigh-Durham weather station (317069), the only weather station that had these data. The historical data set contained dew point temperatures from 1948 to the present. Current conditions for dew point temperatures were determined by developing graphs to show the fluctuation in monthly dew points over time. This was done to show the variation in historical dew point temperatures and to pinpoint the most relevant, but accurate time series on which to base the current conditions. Thirteen plots were created, one for the historical annual average and twelve plots for each individual monthly average. Due to the fluctuations between highs and lows in the annual average (in monthly projections) and the highs and lows in the historical average (annual projections), current conditions were based on the average of the years of 1993 and 2013. This 20-year range was chosen because there were 11 low values and 10 high values, compared to the mean value for dew point temperature, suggesting a balanced current condition. Ten year (2003-2013) and 15-year (1998-2013) averages were calculated with close results to the 20-year average, however, the ten and 15-year averages were less accurate than the 20-year average. The 20-year time has 21 data points, with 11 low values and 10 high values, compared to the 15-year time span, which has 16 data points, with 7 low values and 9 high values, and the ten-year time span, which has 11 data points, with 7 low values and 4 high values. Because the 20-year time span has more data points and there is more similarity in the number of high and low values, it is seen to be more accurate than the 15 or ten-year time span. To calculate actual vapor pressure, the dew point temperatures were converted from degrees Celsius to Kelvin and used in the formula, $e_a = 6.11 \times 10^{\frac{(7.5 \times T_d)}{(237.3+T_d)}}$. Here T_d stands for dew point temperature. The calculated actual pressure is measured in inches of Mercury (in. of Hg).

Wind speed is also required to calculate evaporation. Wind speed was also obtained from the same weather station as dew point temperatures, the Raleigh-Durham Station (317069). Monthly averages from 1948 to present were averaged to determine total seasonal average, which served as the current conditions.

Based on the equation $\Delta S = P - E$, each season has characteristic storage levels (gauge height), precipitation, and evaporation values, which serve as current conditions. The IPCC AR4 precipitation and temperature change projections are evaluated to determine changes in storage from current conditions in order to calculate potential changes in water supply.

Two types of data are not available to calculate future water evaporation, future dew point temperatures or future water temperature. Therefore historical data was used to represent these variables. To calculate future water temperature, a regression was run between historical water temperature seasonal averages and historical air temperature seasonal averages. This was undertaken because it would be wrong to assume that water bodies will stay at current temperatures while the air temperatures increase. Table 4.10 shows the linear equations and R-squared values for the relationship between historical water and air temperatures for each season. The correlations between air and water temperatures for each season are strong enough to use for future water temperature change predictions.

Table 4.10. Linear Equation and R-squared Value for the Seasonal Correlations between Air and Water Temperature.

Water and Air Temperature Correlations by Season		
Season	Linear Equation	R-squared Value
Spring	$y= 1.0796x + 0.7698$	$R^2 = 0.93067$
Summer	$y= 0.73x + 0.89041$	$R^2 = 0.89041$
Autumn	$y= 0.979x + 5.1043$	$R^2 = 0.95774$
Winter	$y= 0.6472x + 4.6477$	$R^2= 0.67322$

To calculate the change in water temperature in the future, seasonal temperature variations based on the three climate change scenarios were input into the linear equations to calculate the temperature change of the water. This gives a best-case, mean-case, and worst-case water temperature change value for each season. These new temperature changes were input to the equation

$e_0 = 6.11 \times 10^{\frac{(7.5 \times T)}{(237.3+T)}}$ to calculate future saturation vapor pressures. Before the temperatures can be input into the equations, they need to be converted from degrees Celsius to Kelvin. This value is given in millibars, so to convert it to inches, it multiplied by 0.0295300 (Petty, 2004)

Future dew point temperatures were determined using historical dew point temperatures. Three dew point change values were created for each season to align with best-case, mean-case, and worst-case changes in air temperature. The best case scenario would be for higher dew point temperatures because higher dew point temperatures with increased water temperature account for lower evaporation rates. The data show that, on average, for each month, there were eight peaks above the mean dew point temperature and eight troughs below the mean dew point temperature. Therefore, the values of the eight peaks serve as a best- case for each month and the values of the eight troughs serve as a worst-case for each month. A mean-case value for each month was calculated by using the average for all the historical data for each month. These monthly values, for each case, were used to make seasonal averages. Each seasonal dew point value for each scenario was put into the equation $e_a = 6.11 \times 10^{\frac{(7.5 \times T_d)}{(237.3+T_d)}}$ to calculate the actual vapor pressure. This value also needs to be converted to inches, just as was done for saturation vapor pressure (Petty, 2004).

To calculate the change in water availability, the equation ΔS= P – E is used. To solve for the change in storage, the net change from current to projected change for both precipitation and temperature are calculated. Table 4.11 provides an example of net change in precipitation and temperature from current spring conditions to best-case spring conditions. Once the net changes for each precipitation and temperature scenario are calculated, the value of E is subtracted from the value of P. This value, measured in inches, is divided by 12 to convert the value into units of a foot. Then it is multiplied by the surface area of the reservoir being examined. All the reservoir surfaces areas are measured in acres. When the value in feet is multiplied by the surface area in acres, the new value is in acre-feet which is then converted into millions of gallons per day from which seasonal amounts are calculated. This, then, results in how many millions of gallons of water per day are being lost or gained in a given season compared to normal conditions.

Table 4.11. Net Change in Conditions for Precipitation and Temperature Under Best-Case Scenario for Spring.

Best-Case Scenario for Spring		
	Precipitation	Evaporation
Current Conditions	10.78 in	0.215 in
Future Projections	12.93 in	0.202 in
Net change from Current Conditions	+2.15 in	-0.013 in

Hydraulic Fracturing Analysis

Future predictions of hydraulic fracturing in North Carolina are difficult for two reasons. First, hydraulic fracturing is legal in North Carolina but is not yet being practiced so there is no baseline data for how hydraulic fracturing might affect water resources. Therefore, the analysis is based on current hydraulic fracturing data in the Marcellus Shale region. Second, the shale beds in North Carolina are small in comparison to most of the shale bed developments in the United States. For example, the total available natural gas in the Marcellus shale is 100 times greater than the total available natural gas in North Carolina shale beds. Because of the size of the North Carolina shale beds, it seems that it will be well into the future before hydraulic fracturing is practiced in North Carolina, because it is much less profitable than many other places in the United States. Nonetheless, it is reasonable to assume that hydraulic fracturing or some other water intensive industry will one day take place in this region.

Based on reports from the PA DEP, about 40% of the land that is leased each year actually turns into drilling permits (Bureau of Oil and Gas Management, 2009, 2010, 2011, 2012). Therefore it is reasonable to assume that 40% of the leased acreage will be developed in the two sub-basins in the first year of production. Based on data for Lee County, where the majority of the Sanford sub-basin is located, 6832 acres have already been leased in the county for unconventional gas extraction, or hydraulic fracturing (Lee County, 2013). Using the 40% proportion seen in Pennsylvania, this means that 2732 acres will be developed in the Sanford sub-basin in the first year that hydraulic fracturing is practiced. Because no leasing data are available for counties in the Durham sub-basin, it will be treated the same as the Sanford sub-basin for the first year of production. In the Sanford sub-basin, the first year of production (2732 acres) is 1.86% of the total sub basin (146,530 acres). This same percentage of the Durham sub-basin (405,236 acres) is 7537 acres, the area assumed to be fracked in the first year.

Once the affected land area has been estimated, it is necessary to estimate how many wells will be constructed in the production areas. This was determined using the North Carolina Oil and Gas Study in 2011 (NC DENR, 2012), which gives scenarios on the density of fracking wells per area, which are modeled after hydraulic fracturing sites in the United States, mainly the Marcellus Shale. This report gives three scenarios on well spacing or well density, wells that are 160 acres, 100 acres, and 40 acres apart. The farther wells are apart, the fewer wells there will be in a production area. Therefore in this analysis, 160-acre plots are a best-case scenario, 100-acre plots are a mean-case scenario, and 40-acre plots are a worst-case scenario.

Along with the well density scenarios from the NC Oil and Gas Study (NC DENR, 2012), the report gives scenarios for water demands for each well. These water needs are also modeled from other fracking operations within the United States, including the Marcellus Shale.

The scenarios for water demands given in the reports are 3 million gallons over a 3-day period, 5 million gallons over a 3-day period, or 3 million gallons of water over a 21-day period. The “day period” is how long fracking of one well would last, and the water demand is how much water is needed over the life of the well site. Table 4.12 converts the water demands and time periods for a well into millions of gallons of water per day. For this analysis, the best-case scenario would be 3 million gallons of water over a 21-day period, the mean-case is 3 million gallons of water over a 3-day period, and the worst-case scenario would be 5 million gallons of water over a 3-day period.

Table 4.12. Scenarios of Water Demand per Well per Day.

	Best-Case	Mean-Case	Worst-Case
Duration	21 Days	3 days	3 Days
Water Demands	3 MGD	3 MGD	5 MGD
Water Demands per Day	142,857 Gallons per Day	1 MGD	1.667 MGD

Although the North Carolina Oil and Gas report (NC DENR, 2012) estimates that fracking will take place over a 30-year period, this seems unlikely due to the small size of the shale beds in North Carolina. Furthermore, this report does not give projections on how production will change from year to year. This is important because is it very unlikely that the amount of hydraulic fracturing will stay constant from year to year. This has not been the case in any state where hydraulic fracturing is taking place. However, due to the large basin sizes where hydraulic fracturing is currently practiced, it is impossible to transpose those practice changes through time to model what could happen in North Carolina. The rates of growth in these areas are not feasible for the size of North Carolina’s shale beds. Therefore this analysis only evaluates different scenarios of what the first year of hydraulic fracturing could look like.

The calculation of area of production, the growth of production through time, and the scenarios of well density make it possible to calculate how many wells will take place during the first year and then change through time. To determine how many wells there will be in the first year, the first-year acreage is needed which is divided by the well density number. For example, in the Sanford sub-basin, 2732 acres would be fracked. Using the assumption (in this example) that well density will be 160 acres, we can assume that there will be 17 wells in the first year of production in the Sanford sub-basin ($\frac{2732\ acres}{160\ acres\ per\ well} = 17\ wells$). Table 4.13 shows the number of wells that could be produced in the first year of production in each sub-basin, based on well density scenarios from the NC Oil and Gas report (NC DENR, 2012).

Table 4.13. Scenarios of Wells Based on Well Density.

Sanford sub-basin	First Year 2732 acres developed		
	Number of Wells		
Year	160 acre Spacing	100 acre Spacing	40 acre Spacing
First	17	27	68
Durham sub-basin	First Year 7537 acres developed		
	Number of Wells		
Year	160 acre Spacing	100 acre Spacing	40 acre Spacing
First	47	75	189

The next step in this analysis is to apply the water demands for each of these well density scenarios through time. The water scenarios are overlaid on the well pad density scenarios. Table 4.14 shows the water demand scenarios in the Sanford sub-basin and Table 4.15 shows the water demand scenarios for the Durham sub-basin. In these tables, 1 MGD stands for the scenario of 3 million gallons over 3 days, 1.667 MGD stands for 5 million gallons over 3 days, and 0.143 MGD stands for 3 million gallons over 21 days. These tables only account for how much water is needed to frack each well and not how much water is needed to drill each well. According to Gregory et al. (2011), the drilling stage of hydraulic fracturing can use anywhere from 105,669 gallons to 1,056,688 gallons of water. For the purpose of this analysis, the median value (581,179) gallons will be used, which is added to the water demands of each well. The water demands for drilling will be the same for each well, regardless of the water demands for the hydraulic fracturing.

Table 4.14. Amount of Water Needed Depending on Well Density in Sanford Sub-basin.

Sanford sub-basin	160 Acre Well Spacing			
Year	Number of Wells	1 MGD	1.667 MGD	0.143 MGD
First	17	17.00	28.34	2.43
	100 Acre Well Spacing			
First	27	27.00	45.01	3.86
	40 Acre Well Spacing			
First	68	68.00	113.36	9.71

Table 4.15. Amount of Water Needed Depending on Well Density in Durham Sub-basin.

Durham sub-basin	160 Acre Well Spacing			
Year	Number of Wells	1 MGD	1.667 MGD	0.143 MGD
First	47	47.00	78.35	6.71
	100 Acre Well Spacing			
First	75	75.00	125.03	10.71
	40 Acre Well Spacing			
First	189	189.00	315.06	27.00

The next part of this analysis accounts for yearly production. It is assumed that wells will not be fracked simultaneously. For example, if a well drill lasts for 3 days, there will be no other wells being fracked at the same time. The assumption used here is that the next well will start after the previous well is finished. However, in order to keep fracking water demands in line with annual and seasonal water demands, it is also assumed that wells that are started in a given year are completed in that year. Therefore, as seen in Table 4.15, there are 189 wells in the first year of production in the Durham sub-basin with well density at 40 acres per well, all of which need to be fully fracked by the start of the next year. To calculate overlap, the number of wells is divided by 365 to determine how many wells overlap per day to finish production in one year's time. Table 4.16 accounts for fracking overlap in the Sanford sub-basin and Table 4.17 accounts for fracking overlap in the Durham sub-basin.

Table 4.16. Continuous Days of Fracking and Wells per Day Based on Well Density Scenarios in the Sanford Sub-basin.

Sanford sub-basin	160 Acre Well Spacing				
		3 Days of Fracking		21 Days of Fracking	
Year	Number of Wells	Days of Fracking	Wells per day overlap	Days of Fracking	Wells per day overlap
First	17	51	-	357	-
	100 Acre Well Spacing				
First	27	81	-	567	1.55
	40 Acre Well Spacing				
First	68	204	-	1428	3.91

Table 4.17. Continuous Days of Fracking and Wells per Day Based on Well Density Scenarios in the Durham Sub-basin.

Durham sub-basin	160 Acre Well Spacing				
		3 Days of Fracking		21 Days of Fracking	
Year	Number of Wells	Days of Fracking	Wells per day overlap	Days of Fracking	Wells per day overlap
First	47	141	-	987	2.70
	100 Acre Well Spacing				
First	75	225	-	1575	4.32
	40 Acre Well Spacing				
First	189	567	1.55	3969	10.87

The final component of this analysis is to evaluate how these projections will affect Raleigh and Durham's water supplies. According to the data in a Susquehanna River Basin Commission (SRBC) report in 2013, hydraulic fracturing water demands are particularly more impactful on local water. Because the Raleigh-Durham water supplies are closer to the Durham sub-basin than the Sanford sub-basin, it is expected that the water demands in the Durham sub-basin will be more taxing on Raleigh's and Durham's water supplies than will the demands in the Sanford sub-basin. Three scenarios were developed based on potential water demand for each sub-basin and the proportional demands on Raleigh-Durham's water supplies using best, mean, and worst-case scenarios (Table 4.18). A best-case scenario is when Raleigh-Durham's water supply is needed to meet 50% of the fracking demands in the Durham sub-basin and 0% of the fracking demands in the Sanford sub-basin. In the mean-case scenario, Raleigh-Durham's water supply is needed to meet 75% of the fracking demands in the Durham sub-basin and 25% of the fracking demands in the Sanford sub-basin. And, in the worst-case scenario, Raleigh-Durham's water supply is needed to meet 100% of the fracking demands in the Durham sub-basin and 50%

of the fracking demands in the Sanford sub-basin. In each of these, it is assumed that Raleigh and Durham will contribute equal amounts of water to meet the demands of fracking.

Table 4.18. Scenarios of Fracking Water Demands Needed from Raleigh's and Durham's Water Supplies.

1 Million Gallons of Water (3 Million gallons of water over 3 days)			
Daily Withdrawals	0% / 50% Needed	25% / 75% Needed	50% / 100% Needed
Sanford	0	250,000	500,000
Durham	500,000	750,000	1,000,000
Total	500,000	1,000,000	1,500,000
Water Demanded From each City's Supply	250,000	500,000	750,000

Evaluating the Factors

In order to evaluate the relative impacts of population growth, climate change, and increased industrial demands through fracking, seasonal demand changes are used as the foundation for water supply variation. Once this has been established, impacts from climate change and hydraulic fracturing will be applied to the seasonal water supply variations. This leads to four different sets of results: 1. seasonal demand change, 2. seasonal demand change with climate change impacts, 3. seasonal demand change with the addition of hydraulic fracturing, and 4. seasonal demand change with climate change impacts and the addition of hydraulic fracturing. The first analysis addresses the impacts of population growth alone, with seasonal variability.

The second analysis, seasonal demand changes with climate change impacts, is relatively straightforward. Each climate change scenario was evaluated to find the change in storage capacity for each season in the future due to climate change projections of precipitation and temperature. The storage capacity change was based on the three scenarios from the IPCC's AR4. Because there are three scenarios and four seasons, that means that there should be a best-case, mean-case, and worst-case impact on water supply for each season. Each of these scenarios for water supply was added to the seasonal demand changes. This combination of change in demand and change in water supply leads to multiple results on how the relationship of supply and demand could fluctuate in the future, with only changes in climate.

The third analysis addresses the addition of fracking demands added to the projected industrial demands from the LWSP's. The new industrial demand is then added to seasonal demand changes. This shows how the various fracking scenarios will impact total seasonal demand, to evaluate if any seasons drastically change in demand, which could cause demand to outstrip available water supply.

The fourth analysis, incorporation of all three factors, is a combination of analyses two and three. Once the seasonal variability of demand versus supply due to climate change scenarios was evaluated, the fracking scenarios were added to total demand projections, as mentioned above. In combination, these analyses provide a comprehensive view of potential stresses on the water systems of Raleigh and Durham, fostering understanding of the future sustainability of those systems.

CHAPTER 5: RESULTS

This chapter presents the results of this research, in which there are five sections: 1. results for population growth and seasonal variation, 2. results for population growth and climate change, 3. results for population growth and change in industrial demand, 4. results for population growth, climate change, and industrial demand, and 5. comparison of factor impacts on a one-year time frame. The first 4 sections outline the impacts of each factor through time. Section 5 compares the impacts of all the scenarios in one year to see the extent to which each factor impacts water availability. These sections illustrate how individual and combined factor simpact water supply in the future for Raleigh-Durham, North Carolina. This chapter covers only the results for the best-case and worst-case scenarios for each analysis.

Population Growth and Seasonal Variation

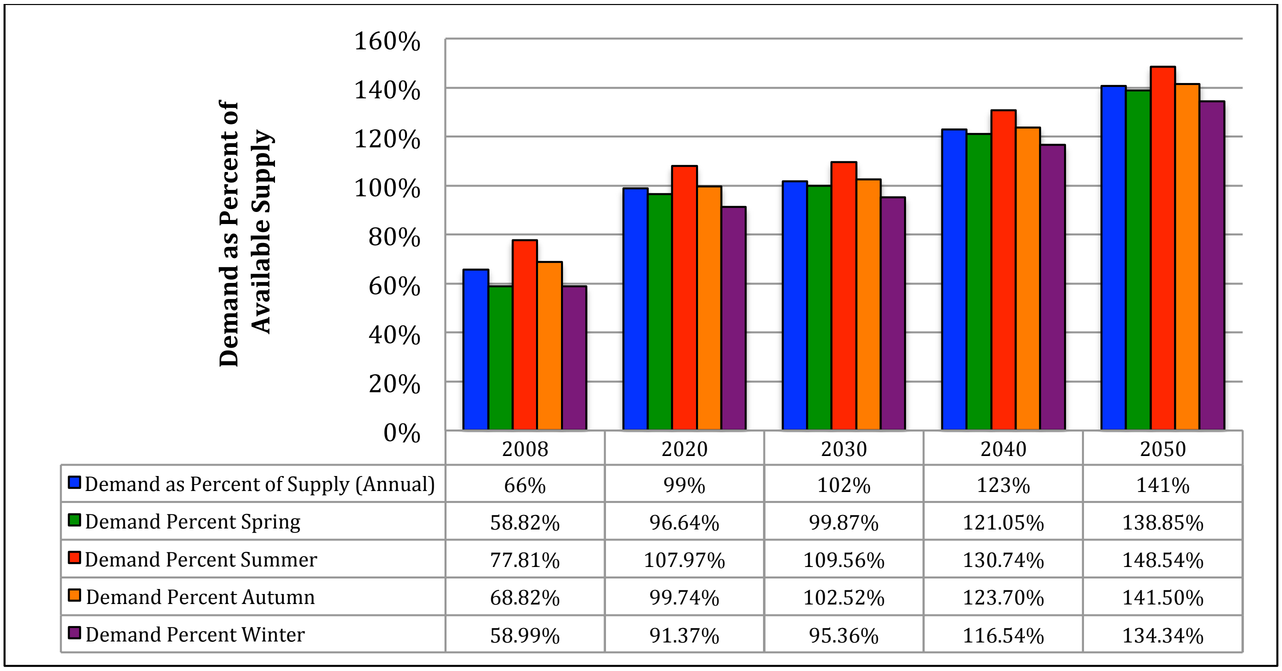
As population grows in the future, water demands increase. This holds true for Raleigh and Durham; however, the rate of population growth and the domestic water demands are different for both Raleigh and Durham as seen in the LWSP projections for 2008 and 2013. The 2013 LWSPs project that, for both cities, population will grow at increasing rates but will use less water per person compared to the 2008 LWSP projections, which show slower rates of population growth in the future, but higher per capita water use (Table 5.1). As an example, looking at the year 2050 for each projection of each city, the population is lower in the 2008 projections but the domestic demands are higher compared to the 2013 projections.

Table 5.1: Differences in Population Growth and Domestic Demand from LWSPs 2008 and 2013 for Raleigh and Durham (NC DWR, 2013a, b).

	2008	**2020**	**2030**	**2040**	**2050**
Year-Round Population	435,000	629,255	765,125	926,473	1,060,472
Domestic Demand (mgd)	27.57	43.62	53.16	64.88	72.45
Population Growth and Domestic Demand (2013 Projection) for Raleigh					
	2013	**2020**	**2030**	**2040**	**2050**
Year-Round Population	497,000	683,300	844,500	995,700	1,225,700
Domestic Demand (mgd)	19.99	36.45	44.26	51.67	58.12
Population Growth and Domestic Demand (2008 Projection) for Durham					
	2008	**2020**	**2030**	**2040**	**2050**
Year-Round Population	232,226	257,162	288,271	314,127	329,280
Domestic Demand (mgd)	12.633	17.23	19.314	21.047	22.062
Population Growth and Domestic Demand (2013 Projection) for Durham					
	2013	**2020**	**2030**	**2040**	**2050**
Year-Round Population	262,725	286,419	329,421	372,423	415,425
Domestic Demand (mgd)	11.205	15.47	17.46	19.37	21.19

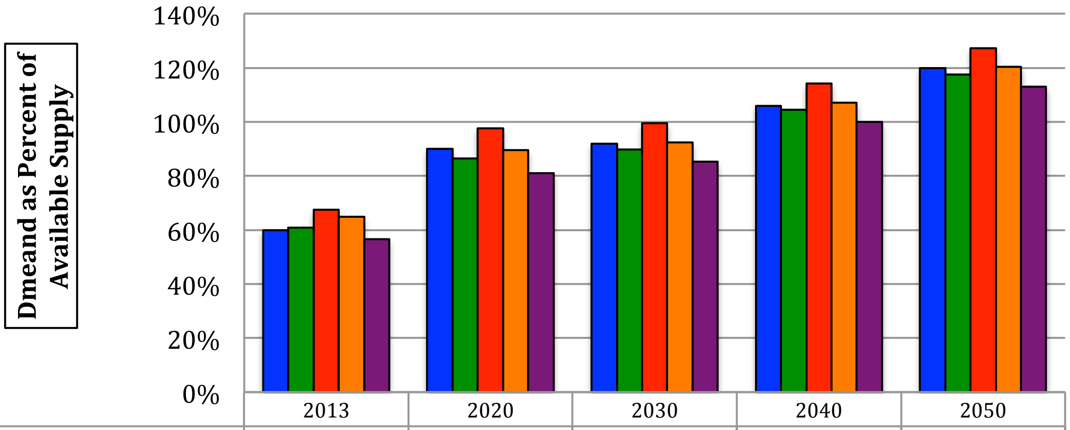
Table 5.1 only gives the annual demand changes into the future. As mentioned before, it is important to calculate the seasonal variability in both water demand and water supply, because neither stays static throughout the year. However, it is worth noting that water supplies for each of the cities stays static through time, in each of the LWSP projections. Thus, water supplies are static through all of these results, except when the impacts of climate change are accounted for. Figures 5.1 and 5.2 show the seasonal variability in total water demands, represented as demand as a percentage of supply, for Raleigh, and Figures 5.4 and 5.5 present the same for Durham. In each scenario for both cities, the summer and autumn demands are higher than the annual average, whereas winter and spring demands are lower than the annual average.

For Raleigh, the summer and autumn water demands start to outstrip supply by 2030 in the 2008 projection, whereas in the 2013 projections none of the seasons in 2030 are projected to outstrip supply, although summer comes close at 99.42% demand versus supply. In both projections, from 2040 onward, all seasonal water demands are higher than available supply. However, it should be noticed that the demand versus supply percentages are higher in the 2008 projections for Raleigh, suggesting that this scenario provides a worse outcome for water availability than the 2013 projections.



	2008	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	66%	99%	102%	123%	141%
🟩 Demand Percent Spring	58.82%	96.64%	99.87%	121.05%	138.85%
🟥 Demand Percent Summer	77.81%	107.97%	109.56%	130.74%	148.54%
🟧 Demand Percent Autumn	68.82%	99.74%	102.52%	123.70%	141.50%
🟪 Demand Percent Winter	58.99%	91.37%	95.36%	116.54%	134.34%

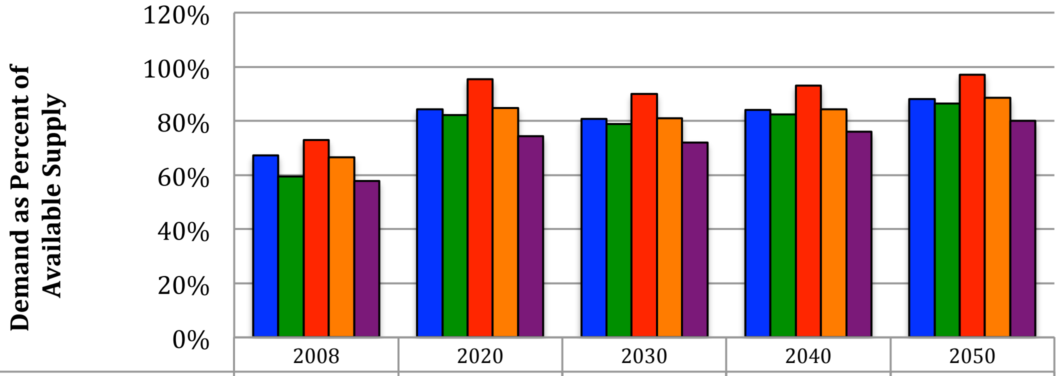
Figure 5.1. Demand as a Percentage of Supply for Raleigh Based on LWSP 2008.



	2013	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	60%	90%	92%	106%	120%
🟩 Demand Percent Spring	60.94%	86.38%	89.73%	104.53%	117.61%
🟥 Demand Percent Summer	67.40%	97.71%	99.42%	114.21%	127.30%
🟧 Demand Percent Autumn	64.79%	89.47%	92.38%	107.17%	120.25%
🟪 Demand Percent Winter	56.55%	81.10%	85.22%	100.01%	113.09%

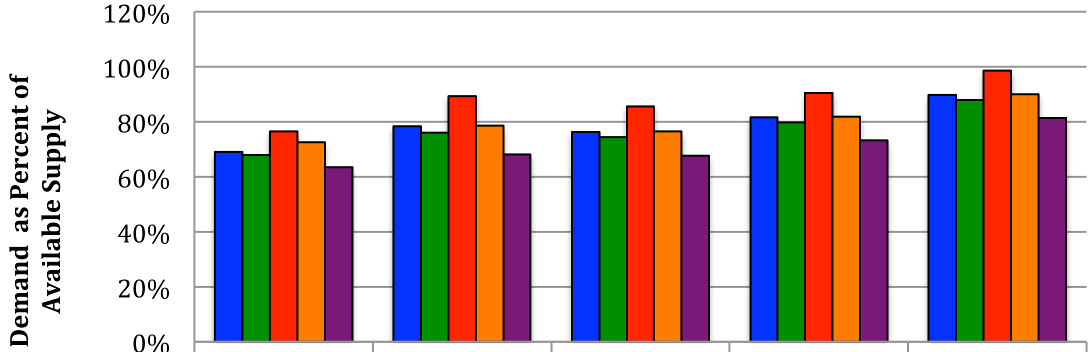
Figure 5.2. Demand as a Percentage of Supply for Raleigh Based on LWSP 2013.

On the other hand, in Durham does not outstrip water supply by 2050 in either projection. Most water demands stay below 90% of supply until 2050. Given these data, the 2008 projections for each city serve as a worst-case scenario for population growth and increasing water demands, whereas the 2013 projections for each city serve as a best case scenario.



	2008	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	67%	84%	81%	84%	88%
🟩 Demand Percent Spring	59.38%	82.14%	78.82%	82.35%	86.41%
🟥 Demand Percent Summer	72.87%	95.32%	90.07%	93.12%	97.17%
🟧 Demand Percent Autumn	66.66%	84.69%	81.00%	84.43%	88.49%
🟪 Demand Percent Winter	57.84%	74.27%	72.10%	75.92%	79.98%

Figure 5.3. Demand as a Percentage of Supply for Durham Based on LWSP 2008.

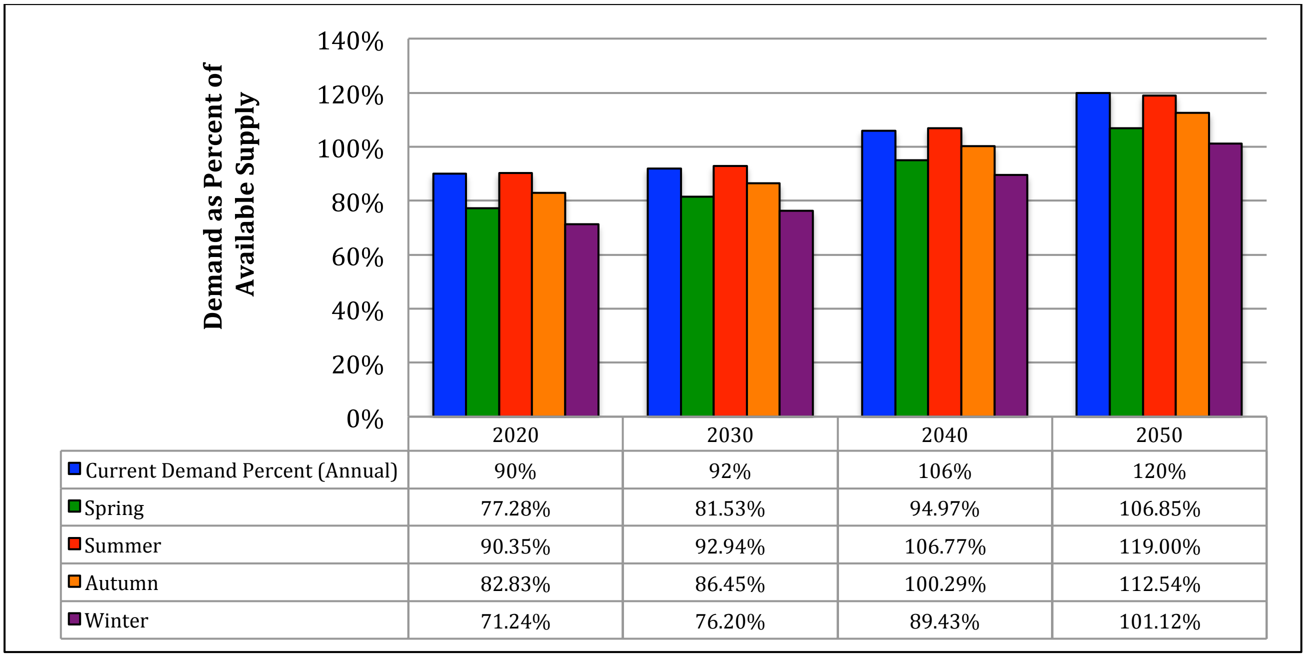


	2013	2020	2030	2040	2050
🟦 Demand as Percent of Supply	69%	78%	76%	82%	90%
🟩 Demand Percent Spring	67.90%	76.09%	74.36%	79.74%	87.89%
🟥 Demand Percent Summer	76.61%	89.27%	85.61%	90.51%	98.66%
🟧 Demand Percent Autumn	72.60%	78.64%	76.54%	81.83%	89.98%
🟪 Demand Percent Winter	63.39%	68.22%	67.64%	73.31%	81.46%

Figure 5.4. Demand as a Percentage of Supply for Durham Based on LWSP 2013.

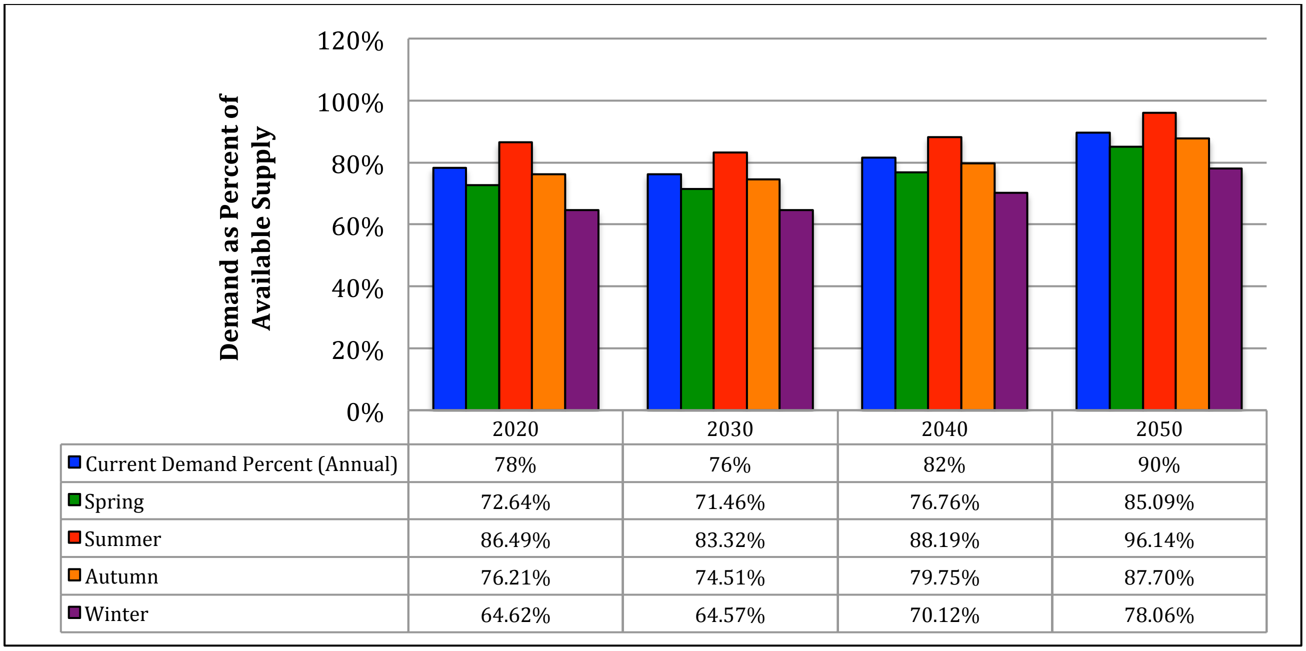
Population Growth and Climate Change

This section presents the results of analysis of the impacts of precipitation and temperature change in the future, due to climate change. The net changes in precipitation and water evaporation, compared to current conditions, were calculated to find change in future water supply. These changes in supply were then added to the annual supply for each projection (2008 and 2013) in both cities. The best-case climate change projections from AR4 are applied to the 2013 LWSP projections to give a best-case scenario of population growth and climate change impacts on water supply. The worst-case climate change projections from AR4 are applied to the 2008 LWSP projections for a worst-case case scenario for population growth and climate change impacts on water supply. Figures 5.5 and 5.6 show the best-case change in supply for both Raleigh and Durham, respectively. Figures 5.7 and 5.8 show the worst-case change in supply for Raleigh and Durham, respectively.



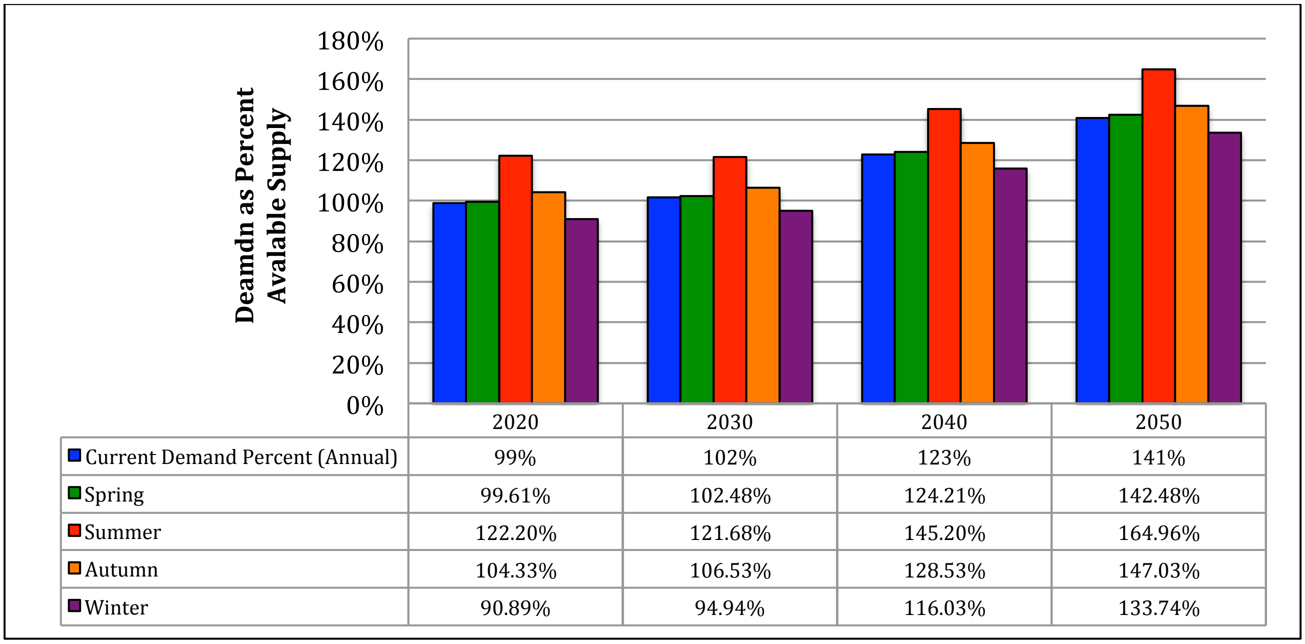
	2020	2030	2040	2050
🟦 Current Demand Percent (Annual)	90%	92%	106%	120%
🟩 Spring	77.28%	81.53%	94.97%	106.85%
🟥 Summer	90.35%	92.94%	106.77%	119.00%
🟧 Autumn	82.83%	86.45%	100.29%	112.54%
🟪 Winter	71.24%	76.20%	89.43%	101.12%

Figure 5.5. Best-Case Climate Change Scenario Applied to Raleigh's 2013 LWSP Projection.



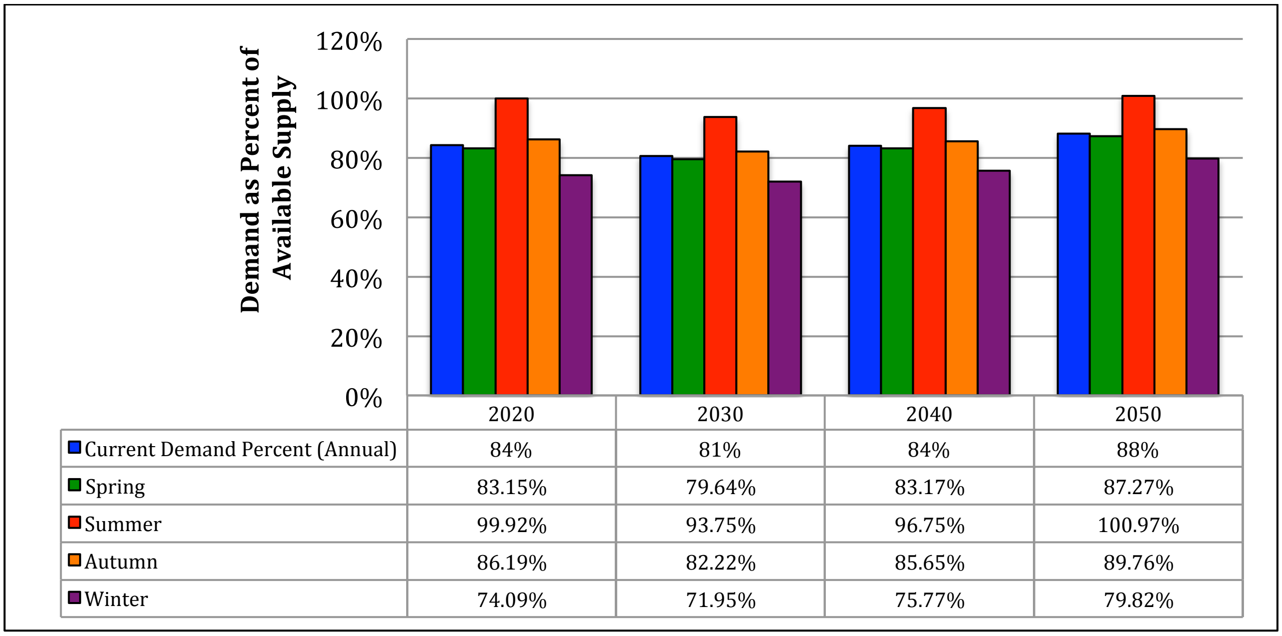
	2020	2030	2040	2050
🟦 Current Demand Percent (Annual)	78%	76%	82%	90%
🟩 Spring	72.64%	71.46%	76.76%	85.09%
🟥 Summer	86.49%	83.32%	88.19%	96.14%
🟧 Autumn	76.21%	74.51%	79.75%	87.70%
🟪 Winter	64.62%	64.57%	70.12%	78.06%

Figure 5.6. Best-Case Climate Change Scenario Applied to Durham's 2013 LWSP Projection.



	2020	2030	2040	2050
🟦 Current Demand Percent (Annual)	99%	102%	123%	141%
🟩 Spring	99.61%	102.48%	124.21%	142.48%
🟥 Summer	122.20%	121.68%	145.20%	164.96%
🟧 Autumn	104.33%	106.53%	128.53%	147.03%
🟪 Winter	90.89%	94.94%	116.03%	133.74%

Figure 5.7. Worst-Case Climate Change Scenario Applied to Raleigh's 2008 LWSP Projection.



	2020	2030	2040	2050
🟦 Current Demand Percent (Annual)	84%	81%	84%	88%
🟩 Spring	83.15%	79.64%	83.17%	87.27%
🟥 Summer	99.92%	93.75%	96.75%	100.97%
🟧 Autumn	86.19%	82.22%	85.65%	89.76%
🟪 Winter	74.09%	71.95%	75.77%	79.82%

Figure 5.8. Worst-Case Climate Change Scenario Applied to Durham's 2008 LWSP Projection.

Considering the best-case scenario for Raleigh, demand versus supply is alleviated due to less evaporation and higher precipitation amounts. Although both summer and autumn outstrip supply in 2040, it is not until 2050 that demand in all seasons outstrips supply. Comparing this to just population growth related water demands, all seasons outstrip supply in 2040 in the Raleigh 2013 projection.

The best-case climate change scenario lessens the impacts of increasing water demands due to population growth because there is an increase in available water supply. However, the best-case climate scenario adds less water supply in Durham than in Raleigh. This is due to the size (acreage) of the water sources of Durham. The net gain or loss in water due to evaporation and precipitation is the same between Raleigh and Durham, but because the surface area of Raleigh's water supply (Falls Lake) is much larger than Durham's water supplies (Lake Michie, Little River Lake, and Jordan Lake), the gain or loss in mgd to the system is larger in Falls Lake compared to Lake Michie, Little River Lake, and Jordan Lake. Nonetheless, in no year does demand outstrip supply in Durham. Further, the best-case climate change scenario lessens the effect of increasing water demands by about 2-3% compared to just population growth effects on water supply.

The worst-case climate change for Raleigh severely exacerbates the growing population water demands. Instead of demand outstripping supply in 2040, with just population growth, the worst-case climate change projection shows demand will outstrip supply by 2020 in spring, summer, and autumn. Yet, it will still take until 2040 for winter demands to outstrip supply. However, it is doubtful that the worst-case climate change impacts will happen as early as 2020 due to the projected 5.5°C-6°C increase. This amount of warming in less than a ten year period is highly unlikely.

The worst-case climate change scenario for Durham decreases supply and causes the demand percentage to increase compared to just growing population water demands. Spring, autumn, and winter never outstrip supply in this scenario; however, summer outstrips supply in

2050. This is based on 2008 projections for population growth, in which supply is never outstripped by demand with just population growth. The supply percentages in the worst-case climate change scenario are only slightly higher than just population growth in Durham for the same reason that supply percentages are only slightly lower in the best-case climate change scenario for Durham.

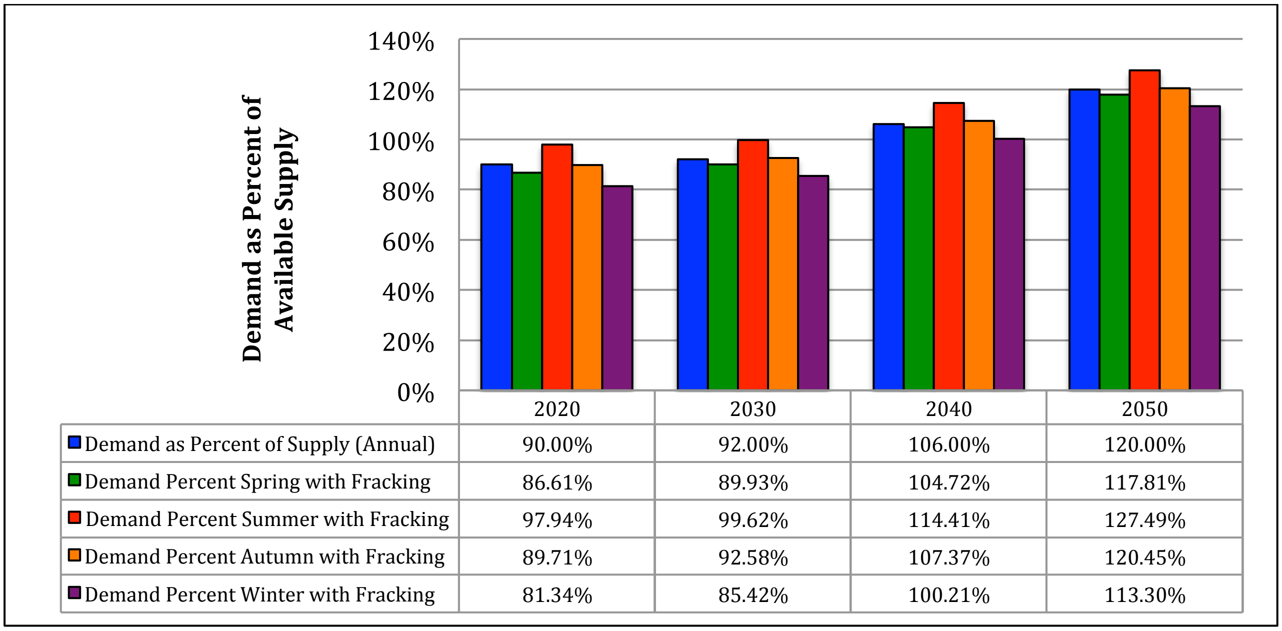
Population Growth and Increased Industrial Demand

This section presents the results of increased water demands due to population growth along with increased industrial water demands from hydraulic fracturing. As with the assessment of climate change on water availability, the 2013 LWSP population projections serve as a basis for the best-case scenario and the 2008 LWSP population projections serve as the basis for the worst-case scenario with the addition of hydraulic fracturing.

The best-case scenario for hydraulic fracturing is low well density (160 acres per well) and water demands of 3 million gallons over a 21-day period. The best-case water demand scenario on Raleigh's and Durham's water supplies is if the Sanford sub-basin requires no water for the hydraulic fracturing needs, while the Durham sub-basin only requires 50% of the hydraulic fracturing water needs from Raleigh and Durham.

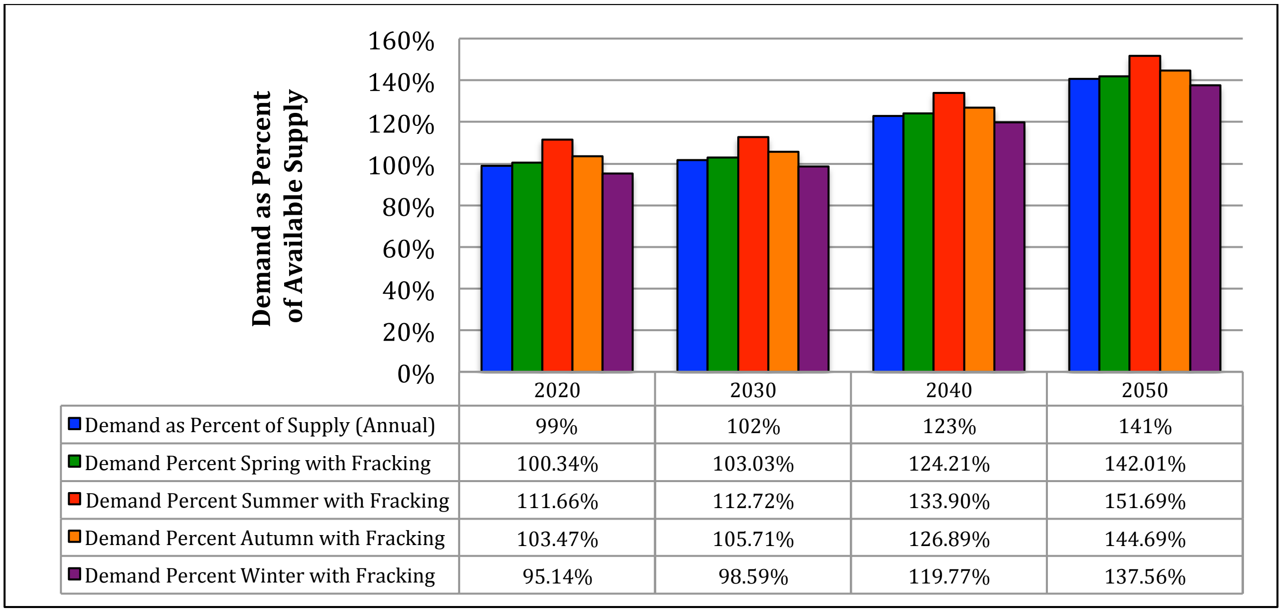
A worst-case scenario for hydraulic fracturing is higher well density (40 acres per well) and water demands of 5 million gallons over a 3-day period. The worst-case water demand scenario on Raleigh's and Durham's water supplies is if the Sanford sub-basin requires 50% of the hydraulic fracturing water demands from Raleigh's and Durham's water supplies, while the Durham sub-basin requires 100% of the hydraulic fracturing water demands from Raleigh's and Durham's water supplies.

Figure 5.9 shows how water demands change in Raleigh with the addition of hydraulic fracturing under a best-case scenario, whereas Figure 5.10 shows how water demands change in Raleigh with the addition of hydraulic fracturing under a worst-case scenario. Figures 5.11 and 5.12 show the same for the city of Durham, respectively. All graphs depict what it would look like if hydraulic fracturing was started in each season of each year. This does not mean that hydraulic fracturing is being practiced in each season; rather it is a model of what it would look like if the first year of hydraulic fracturing happened during a particular season of a particular decade. These analyses account for water needs for both drilling a well and fracking a well.



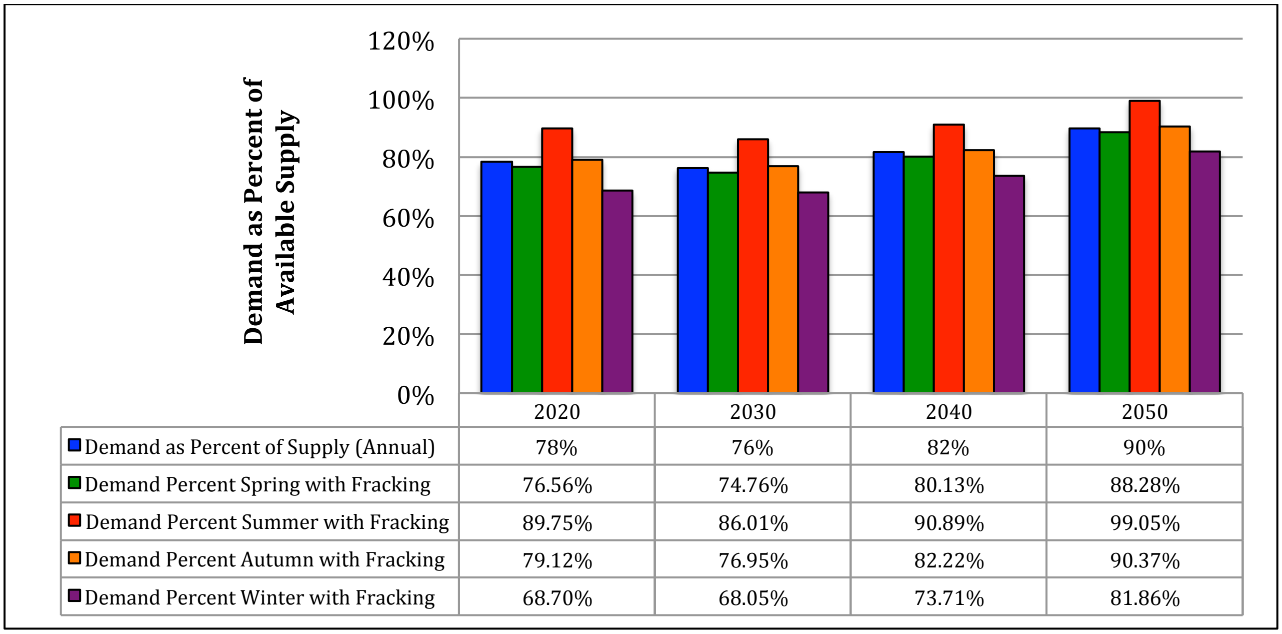
	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	90.00%	92.00%	106.00%	120.00%
🟩 Demand Percent Spring with Fracking	86.61%	89.93%	104.72%	117.81%
🟥 Demand Percent Summer with Fracking	97.94%	99.62%	114.41%	127.49%
🟧 Demand Percent Autumn with Fracking	89.71%	92.58%	107.37%	120.45%
🟪 Demand Percent Winter with Fracking	81.34%	85.42%	100.21%	113.30%

Figure 5.9. Change in Demand as Percent of Supply in Raleigh with Best-Case Population Growth and Best-Case Hydraulic Fracturing Water Demands.



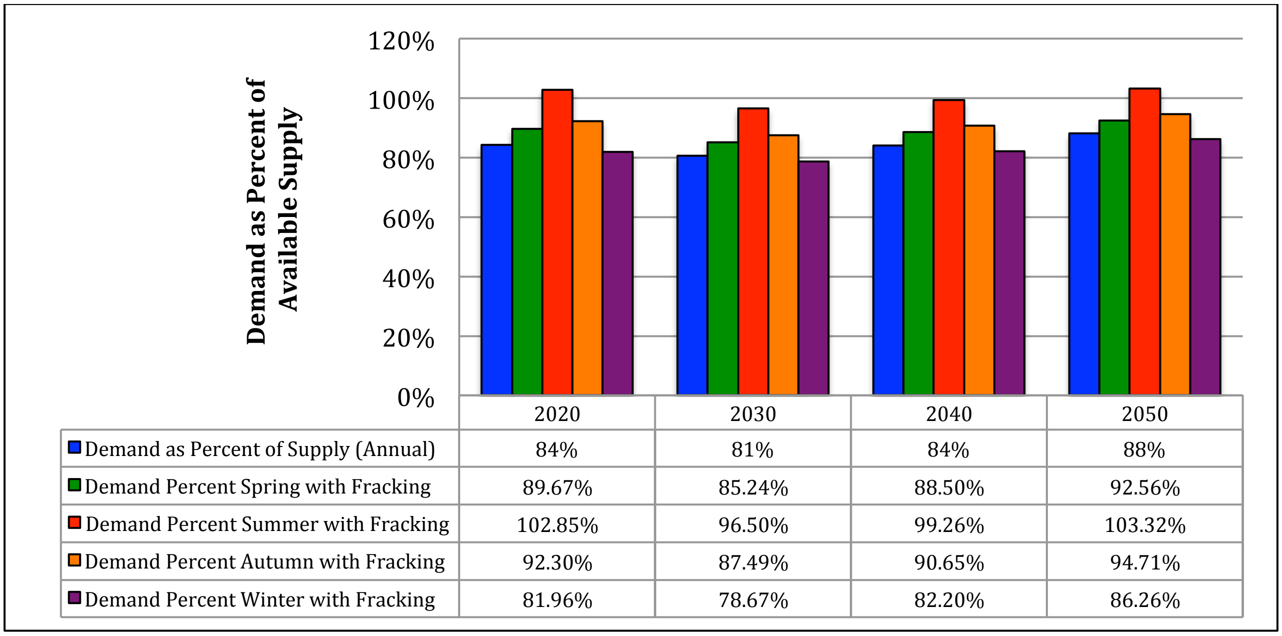
	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	99%	102%	123%	141%
🟩 Demand Percent Spring with Fracking	100.34%	103.03%	124.21%	142.01%
🟥 Demand Percent Summer with Fracking	111.66%	112.72%	133.90%	151.69%
🟧 Demand Percent Autumn with Fracking	103.47%	105.71%	126.89%	144.69%
🟪 Demand Percent Winter with Fracking	95.14%	98.59%	119.77%	137.56%

Figure 5.10. Change in Demand as Percent of Supply in Raleigh with Worst-Case Population Growth and Worst-Case Hydraulic Fracturing Water Demands.



	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	78%	76%	82%	90%
🟩 Demand Percent Spring with Fracking	76.56%	74.76%	80.13%	88.28%
🟥 Demand Percent Summer with Fracking	89.75%	86.01%	90.89%	99.05%
🟧 Demand Percent Autumn with Fracking	79.12%	76.95%	82.22%	90.37%
🟪 Demand Percent Winter with Fracking	68.70%	68.05%	73.71%	81.86%

Figure 5.11. Change in Demand as Percent of Supply in Durham with Best-Case Population Growth and Best-Case Hydraulic Fracturing Water Demands.



	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	84%	81%	84%	88%
🟩 Demand Percent Spring with Fracking	89.67%	85.24%	88.50%	92.56%
🟥 Demand Percent Summer with Fracking	102.85%	96.50%	99.26%	103.32%
🟧 Demand Percent Autumn with Fracking	92.30%	87.49%	90.65%	94.71%
🟪 Demand Percent Winter with Fracking	81.96%	78.67%	82.20%	86.26%

Figure 5.12. Change in Demand as Percent of Supply in Durham with Worst-Case Population Growth and Worst-Case Hydraulic Fracturing Water Demands.

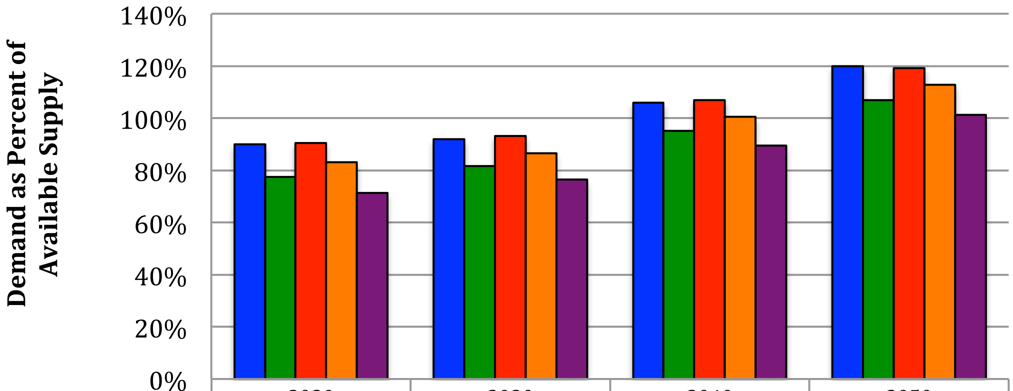
As shown in the Figures 5.9 and 5.11, when the best-case scenarios for population demand change and hydraulic fracturing are combined, the percentage of demand related to supply increases, however, hydraulic fracturing does not drastically impact the demand-supply percentage. Therefore, under these conditions it is safe to say that hydraulic fracturing will impact the water system; however, it will not do so in a way that is more damaging to the system than that of the population growth demands. This is not the same for the worst-case scenario for Raleigh.

Figure 5.10 shows water demand as a percent of supply when the worst-case population growth demand change is coupled with the worst-case hydraulic fracturing scenario. The large water demands for hydraulic fracturing along with the large water demand for growing populations seriously strain the water supply. In the spring, summer, and autumn, demand outstrips supply starting in 2020, compared to 2040 when just analyzing population growth demand. However, this is not the true for the worst-case scenario for Durham.

The worst-case for Durham is shown in Figure 5.12. The addition of a worst-case hydraulic fracturing practice to a worst-case population water demand scenario shows that the demand as a percentage of supply increases for each season. However, summer is the only month that gets close to or actually has water demands that outstrip supply. These worst-case scenarios may become even more severe to the water supply system when climate change impacts are added to this analysis.

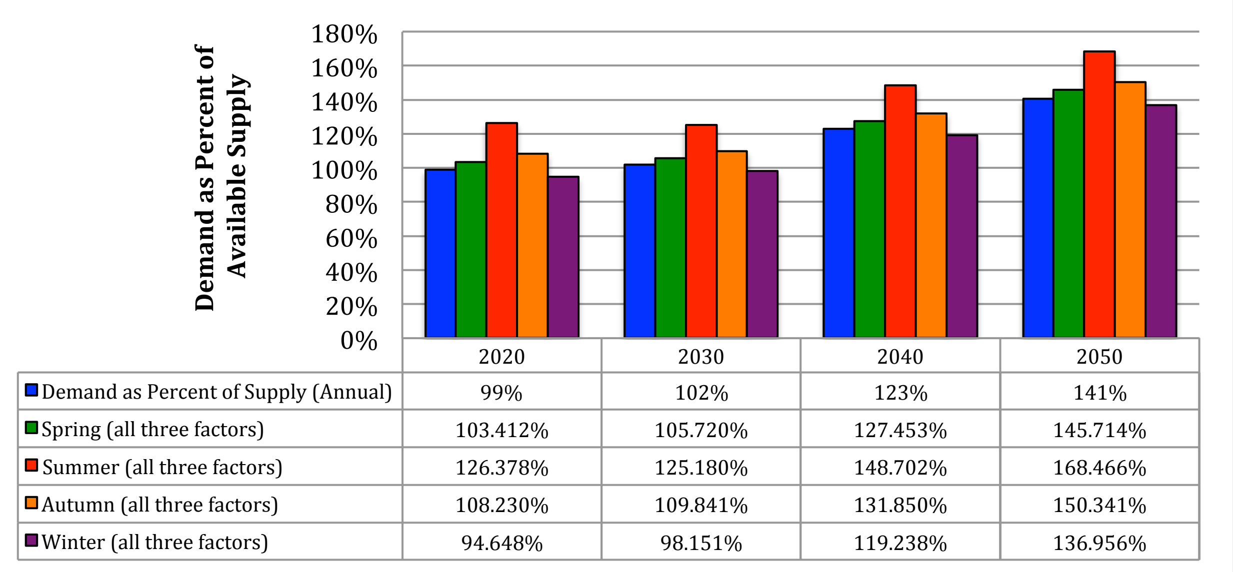
Population Growth, Climate Change, and Industrial Demand, Change

This section addresses how all three factors, combined, impact water supplies in both the best-case and worst-case scenarios. This section is the combination of the results prsented in the previous sections. Figures 5.13 and 5.14 display the best and worst-case combined results for Raleigh, while Figures 5.15 and 5.16 do so, in the same fashion, for Durham.



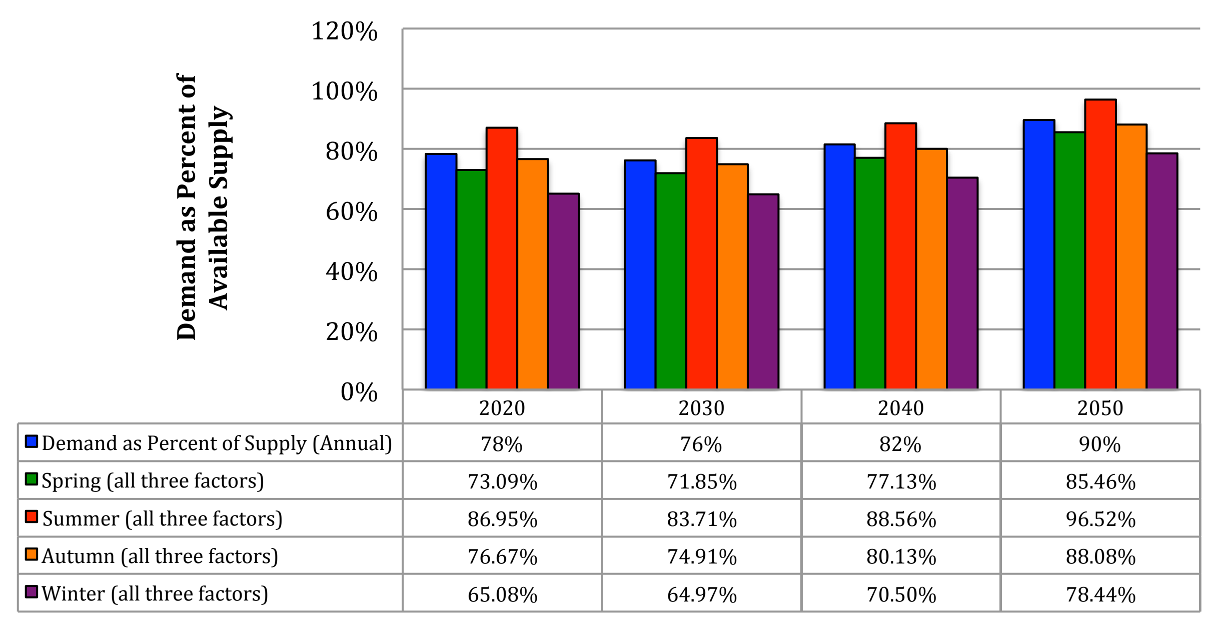
	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	90.00%	92.00%	106.00%	120.00%
🟩 Spring (all three factors)	77.490%	81.708%	95.146%	107.032%
🟥 Summer (all three factors)	90.560%	93.130%	106.957%	119.188%
🟧 Autumn (all three factors)	83.048%	86.639%	100.480%	112.724%
🟪 Winter (all three factors)	71.448%	76.382%	89.608%	101.306%

Figure 5.13. Future Water Availability Based on Best-Case Scenarios of Population Growth, Climate Change, and Hydraulic Fracturing in Raleigh.



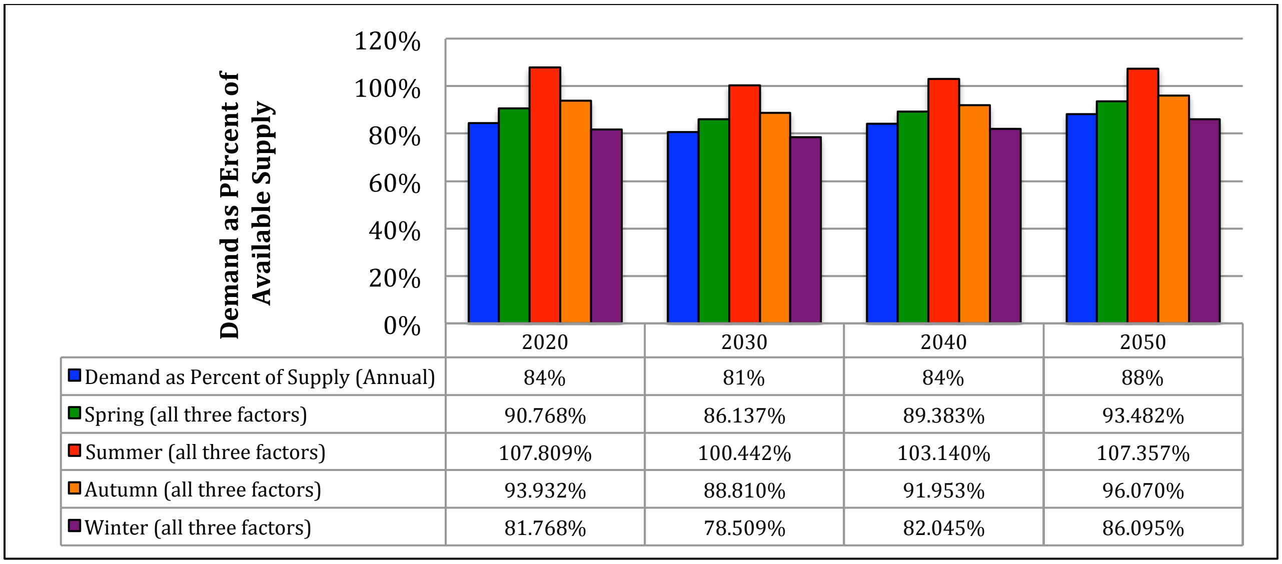
	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	99%	102%	123%	141%
🟩 Spring (all three factors)	103.412%	105.720%	127.453%	145.714%
🟥 Summer (all three factors)	126.378%	125.180%	148.702%	168.466%
🟧 Autumn (all three factors)	108.230%	109.841%	131.850%	150.341%
🟪 Winter (all three factors)	94.648%	98.151%	119.238%	136.956%

Figure 5.14. Future Water Availability Based on Worst-Case Scenarios of Population Growth, Climate Change, and Hydraulic Fracturing in Raleigh.



	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	78%	76%	82%	90%
🟩 Spring (all three factors)	73.09%	71.85%	77.13%	85.46%
🟥 Summer (all three factors)	86.95%	83.71%	88.56%	96.52%
🟧 Autumn (all three factors)	76.67%	74.91%	80.13%	88.08%
🟪 Winter (all three factors)	65.08%	64.97%	70.50%	78.44%

Table 5.15. Future Water Availability Based On Best-Case Scenarios of Population Growth, Climate Change, and Hydraulic Fracturing in Durham.



	2020	2030	2040	2050
🟦 Demand as Percent of Supply (Annual)	84%	81%	84%	88%
🟩 Spring (all three factors)	90.768%	86.137%	89.383%	93.482%
🟥 Summer (all three factors)	107.809%	100.442%	103.140%	107.357%
🟧 Autumn (all three factors)	93.932%	88.810%	91.953%	96.070%
🟪 Winter (all three factors)	81.768%	78.509%	82.045%	86.095%

Table 5.16. Future Water Availability Based On Worst-Case Scenarios of Population Growth, Climate Change, and Hydraulic Fracturing in Durham.

The best-case for Raleigh (Figure 5.13) shows that the combination of population growth, climate change, and hydraulic fracturing impact water supply less than population growth acting alone. This is because the best-case climate change scenario increases water supplies enough to lessen the impacts of population growth and hydraulic fracturing (each in a best case scenario). However, by 2040 both summer and autumn demands outstrip water supply, and in 2050 all of the seasons' demands outstrip supply; yet, the demand percentages are less than they would be with just population growth demands.

As expected, the worst-case impacts are the complete opposite of the best-case results. Higher domestic and industrial demands and less available water supply due to climate change have large impacts on water availability. When all three factors are combined, spring, summer and autumn water demands outstrip supply, and it takes until 2040 for winter demands to outstrip supply. As expected, the percentages of demand versus supply are much higher in a coupled fashion, for each season, when compared to just population growth demands.

Durham follows the same pattern as Raleigh, in that the best-case scenario has fewer impacts on water supply than the worst-case scenario. However, the positive and negative impacts on water supplies that Durham experiences are less extreme than in Raleigh for two reasons. First, Raleigh has higher domestic demands and a faster growing population than Durham; therefore, growing demands are going to have more of an impact on Raleigh than they will on Durham. Second, the surface area of the water supplies of Durham is much smaller than that of Raleigh, which means that changes in water supply availability are going to vary more greatly for Raleigh when precipitation and evaporation rates change in the future. Because of this, in the best-case scenario, Durham's demands do not outstrip supply by 2050, whereas in the worst-case scenario, the summer months from 2020 to 2050 all outstrip supply; however, no other seasons' demands, in either projection, outstrip supply.

Comparison of Factor Impacts on a One-Year Time Frame

The previous sections present a through-time analysis of how each factor could impact water availability. The graphs in these sections did not show in detail how each factor specifically impacted water availably and demand as a percentage of supply. Thus, this section shows how each factor affects water availability in one season of one year in the future. The year 2030 was chosen for this because it is the midway point between present and when the future predictions end in 2050. The season of spring is used in this analysis and uses the same scenarios from the last four sections, in which there is a best-case and worst-case scenario for both Raleigh and Durham. The best-case scenarios for Raleigh and Durham are presented first and are shown in Figures 5.17 and 5.18, respectively.

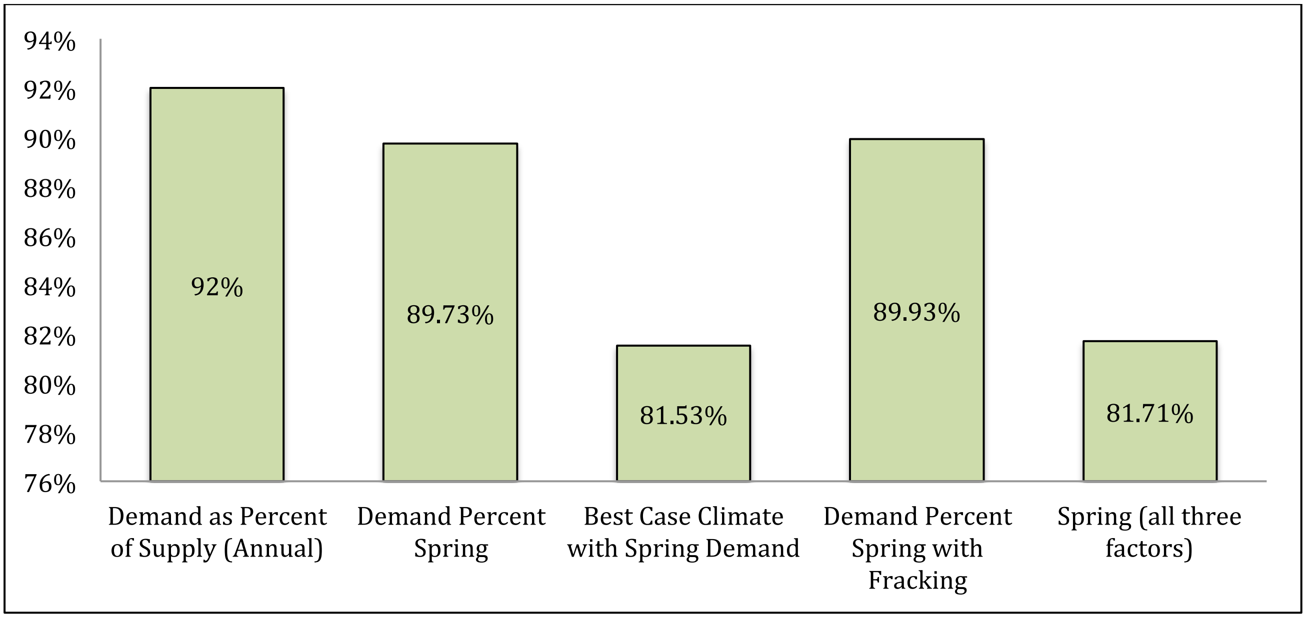


Figure 5.17. Side-By-Side Factor Analysis for Raleigh in Spring 2030, Based on Best-Case Scenario.

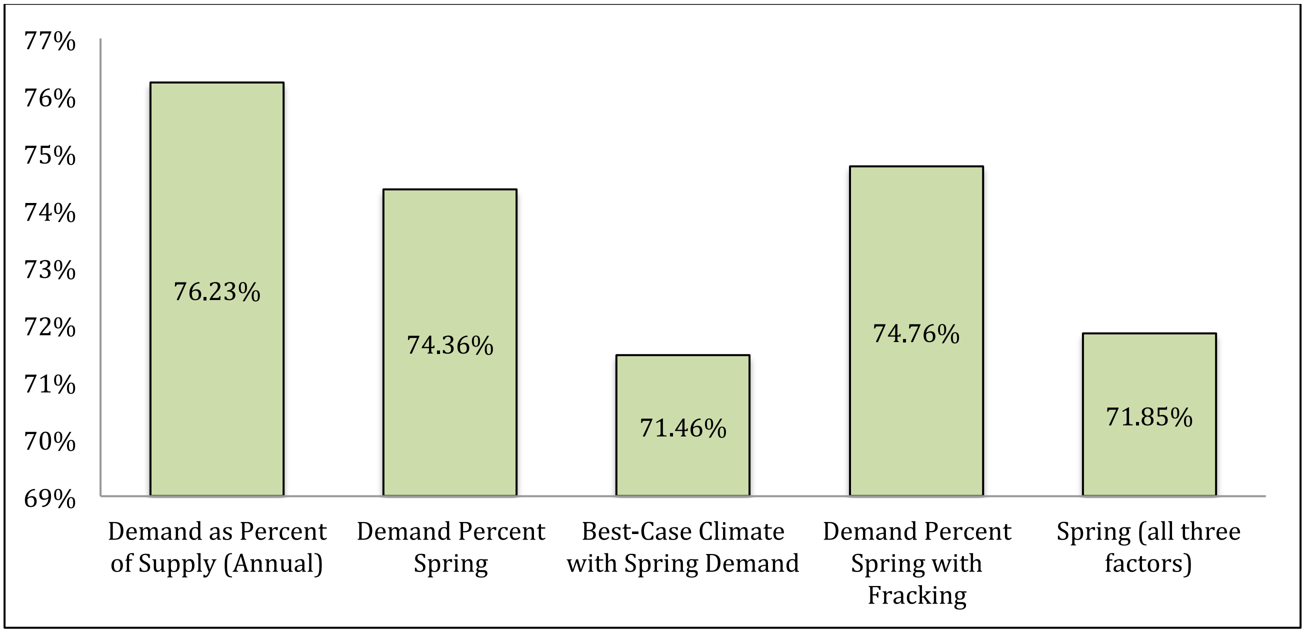


Figure 5.18. Side-By-Side Factor Analysis for Durham in Spring 2030, Based on Best-Case Scenario.

In these graphs, it can be seen that the spring demand as a percent of supply is lower than that of the annual projection. This is supported by the analysis of population growth and seasonal variance. Also, in addition, the climate change factor lowers the spring demand percentage because this climate change scenario increases water supply. With hydraulic fracturing added, it can be seen that the percentage of demand increases in spring from 89.73% to 89.93% in Raleigh and 74.36% to 74.76% in Durham. This shows that under this scenario, hydraulic fracturing does not have a major impact on water supplies. When all three factors are evaluated, it can be seen that the demand percentage is lower than both the projected annual percentage and the spring demand percentage. This is because the climate change factor significantly increases water supply and hydraulic fracturing does not significantly add to the water demands. However, results for worst-case scenarios for Raleigh (Figure 5.19) and Durham (Figure 5.20) in 2030 are quite different.

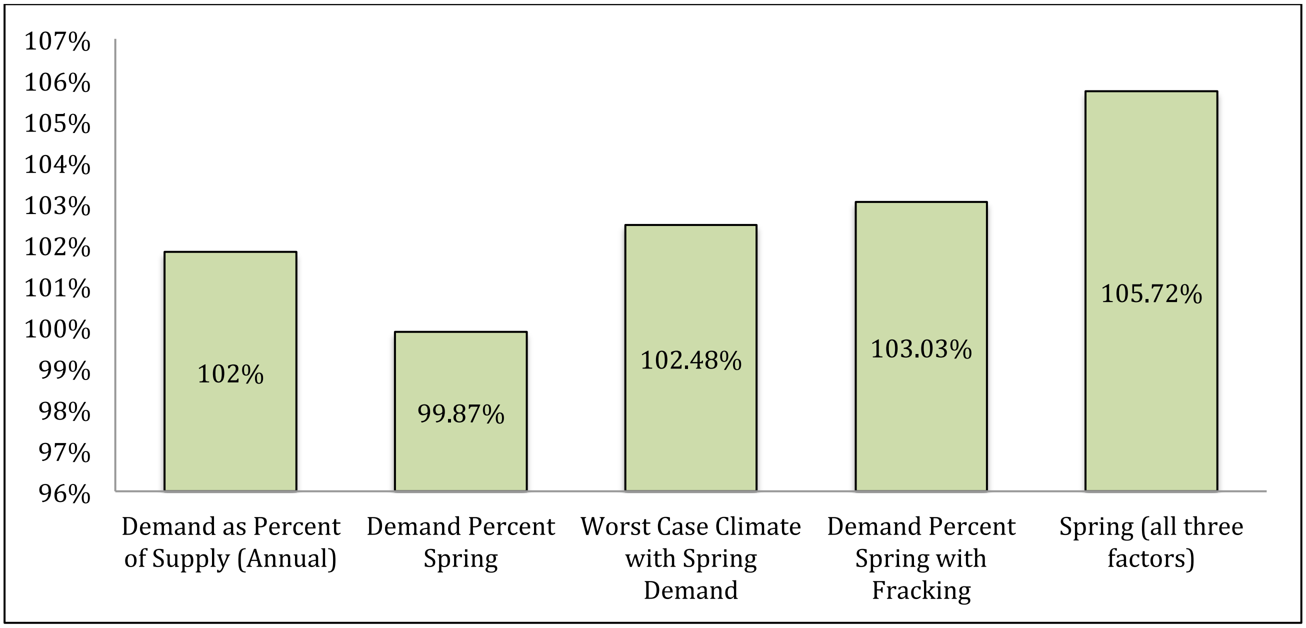


Figure 5.19. Side-By-Side Factor Analysis for Raleigh in Spring 2030, Based on Worst-Case Scenario.

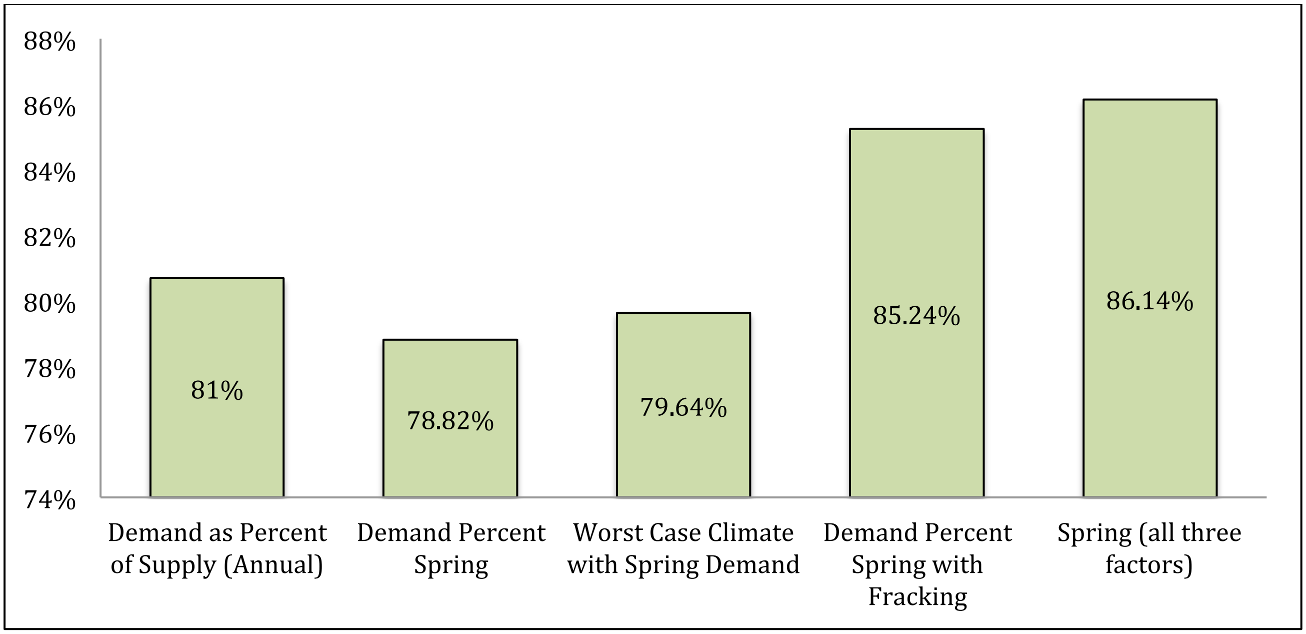


Figure 5.20. Side-By-Side Factor Analysis for Durham in Spring 2030, Based on Worst-Case Scenario.

In both Figures 5.19 and 5.20 it can be seen that spring demand percent is lower than the annual projected demand percent. However, compared to the previous graphs, spring demand percent is the lowest bar on the graphs. This is because the climate change scenario decreases available supply, making the demand versus supply percentage increase from 99.87% to 102.48% in Raleigh and 78.82% to 79.64% in Durham. The worst-case hydraulic fracturing scenario puts more stress on water supply than climate change, due to the intensive water needs. Demand percentage in Raleigh increases from 99.87% to 103.3% and increases in Durham from 78.82% to 85.24%. However, in both Raleigh and Durham, the demand percentage is highest when the factors are combined.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

Discussion

The analysis of future water availability for Raleigh and Durham has shown that it is not a matter of “if” either city will face water supply shortages, but it is more of a question of “when.” Due to Raleigh’s rapidly growing population, its demands will impact supply much more quickly than will be the case for the city of Durham. It was found that Raleigh’s water demands will start to outstrip supply in 2040, without the impacts of climate change or hydraulic fracturing. However, depending on the severity of climate change and the scale of hydraulic fracturing production, water supply could be impacted before 2040. That is why this research had a wide scale of scenarios for each factor, to evaluate a range of multiple potential future outcomes in available water supply.

Although the results show that Raleigh will quickly be facing water availability shortages well before Durham, it does not mean that Durham will not feel future water stress. The scope of this research ends right about the time frame some projections show Durham having seasonal demands (summer) outstripping supply, such as in 2060 in the 2013 LWSP. If Durham’s water demand patterns follow Raleigh’s, it is only a matter time before seasonal demands start to outstrip supply.

Within the scope of this research (present to 2050), two domestic water demand projections were used for each city, the 2013 LWSP as the best-case scenario and the 2008 LWSP as the worst-case scenario. These two projections for each city give a range of how water demands could vary in the future. Both scenarios had Raleigh’s seasonal demands outstripping supply within the time frame of this research. Durham on the other hand, just barely began to feel water supply stress at the end of each projection. This means that Durham might be better off than Raleigh, however, Durham is not free from future water stress.

Future water stress was either alleviated or exacerbated based on different climate change scenarios. The best-case climate change scenario added water to the water supply system, which alleviated demand versus supply percentages into the future. However, in Raleigh, the influx of water created by this scenario did not add enough water to the supply to “cure” water supply issues in the future. It mainly acted as a band-aid to help water supply meet demand until 2050. This outcome was the same for Durham; however, because demands were lower than Raleigh’s, the best-case climate change scenario showed Durham to have more promising demand versus supply percentages.

The worst-case scenario provided the expected, opposite results than the best-case scenarios for water supply. Due to lower precipitation amounts and higher evaporation rates, water supply diminished for both cities. However, Raleigh felt the negative effects of climate change much more than Durham due to higher water demands and the fact that Raleigh’s water supply system was more affected by climate change than was Durham’s system.

Hydraulic fracturing ranged in impacts on water supply given the large range of scenarios. With that being said, it seems that some of the hydraulic fracturing scenarios are more sustainable than others. This means that hydraulic fracturing could be done in North Carolina and have minimal impacts to water supplies for Raleigh and Durham. However, to minimize the realized impacts of hydraulic fracturing on water supply, it should take place sooner rather than later. The farther in the future that hydraulic fracturing is practiced, the more the water supply systems will already be taxed due to increased water demands from a growing population.

It is important to know exactly how hydraulic fracturing will increase the industrial demands of Raleigh and Durham, and thus how hydraulic fracturing changes the total demands of these cities. Table 6.1 shows the percentage that industrial water demands comprise of the total demands, and these percentages would change if hydraulic fracturing were to be added. This table also shows the percentages of industrial demands with and without hydraulic fracturing in the time frame of both 2020 and 2050. It can be seen that industrial demands make up more of the total demand in 2020 than they do in 2050; as time goes on, industrial demands increase, but they comprise much less of the total demand than do the growing residential demands.

Table 6.1. Industrial Demands as Percent of Total Water Demands Under Different Scenarios and Years for Raleigh and Durham.

Scenario	Year	Industrial Demand Percent of Total Demand	
		Without Fracking	With Fracking
Best-case Raleigh	2020	2.5%	2.7%
	2050	2.5%	2.7%
Worst-case Raleigh	2020	2.0%	5.7%
	2050	2.6%	4.8%
Best-case Durham	2020	4.2%	4.8%
	2050	4.5%	5.0%
Worst-case Durham	2020	3.8%	11.7%
	2050	4.3%	11.2%

Indeed, the timing of hydraulic fracturing is especially important in relation to climate change. The IPCC predicts that as the current century continues, the Earth will steadily get warmer. Therefore, the worst-case climate change scenario is more likely to happen in the distant future. If hydraulic fracturing does not happen in this state until farther in the future, the water needed for hydraulic fracturing may not be available because water supplies could be under stress due to high population demands and low recharge from less precipitation and greater evaporation.

Ultimately there is a range of possibilities for how future water supplies could be impacted or how much will be available. This research provides many different scenarios of possible ways the future could play out for Raleigh and Durham, in relation to water supplies. Again, both cities will see water stress in the future due to higher demands. It is just a matter of time when it will happen. Right now it looks as though Raleigh will start to feel the effects of lessened water supplies before Durham.

Limitations to the Research

This research evaluated three different factors that could impact water availability in the future. However, there are limitations to this research that must be addressed. The population data presents the first limitation. All of the data are based on projections, which are limited. Each municipality or county makes these projections and then sends then to NC DWR, which then compiles them. These projections are only as accurate as the planners can make them. As a result, the analyses are only as valid as the projections on which they are based. This holds true for both the analyses of climate change and hydraulic fracturing.

This research used AR4 (2007) to model climate change scenarios. The next report, AR5 has been released in stages (2013-2014), and the updated scenarios on the impacts of climate change for different regions were not released at the time of this research, making AR4 the most updated IPCC report to use. It would be useful to undertake the same analysis with the new data.

Another limitation of this research is future available water that could be added to the Raleigh-Durham water nexus. This research does not account for water supply increase, such as potential inter-basin transfers or the development of new in-basin supplies. The addition of future water supplies will affect the results of this research; however, it is impossible to predict. In addition, the contribution of groundwater to existing or future water supplies was not considered for reasons detailed previously.

The last limitation of this research is length of time hydraulic fracturing takes place in North Carolina. It was impossible to model how hydraulic fracturing will develop in and past the first year in North Carolina. Thus, a limitation of this research is how hydraulic fracturing will impact water availability through time, given that this research does not evaluate how hydraulic fracturing activities will grow or shrink through time.

Conclusions

This research provides a methodology to evaluate population growth water demands, climate change, and increased industrial demands in an urban setting. Moreover this research provides an outline for possible water stress scenarios in the future for Raleigh and Durham, which the local governments could use to inform future planning.

This analysis is helpful to local and state government in three ways. First, it provides insights into new policy options for water supply management. If a local government concludes that it will face water problems in the future, it might start to take risk-management opportunities to lessen future impacts, such as early water conservation methods. This would be much more effective than waiting until the problem is imminent, requiring local governments to react with crisis management.

Secondly, this research has important implications for the North Carolina State Government in policy decisions related to hydraulic fracturing. Because this research gives multiple scenarios and outcomes of hydraulic fracturing and its impacts on water resources, the

State Government could use it to promulgate guidelines on how they want hydraulic fracturing practices to operate in this state in relation to well density, water use rate per well, and where oil and gas companies acquire their water.

Third, this research takes a comprehensive approach to evaluating different water futures. In so doing, it incorporates technical, scientific projections into a management framework. This approach has application to water management and planning in any location. While the specific results of the case study used here are not generalizable, the methods are.

This research deconstructs the notion that the eastern United States should still be considered "water-rich." It is true that the eastern United States has more available water than the arid Western United States; however, the term "water-rich" gives the connotation that water supplies are not a concern in a specific region. This research challenges that notion. Even the southeast United States will face water supply shortages, especially in rapidly growing areas. The good news is that if this idea is met head-on with proactive management techniques, the Southeast United States might not face the water stress issues that the western United States is currently facing.

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APPENDIX A: DATA USED IN ANALYSYS

<table>
<tr><td colspan="4">Raleigh, North Carolina</td></tr>
<tr><td colspan="4">NC DWR 2008</td></tr>
<tr><td>Year</td><td>Population</td><td>Appox. % Increase</td><td>40 Year % Increase</td></tr>
<tr><td>2008</td><td>435,000</td><td>-</td><td rowspan="5">143.8%</td></tr>
<tr><td>2020</td><td>629,255</td><td>44.7%</td></tr>
<tr><td>2030</td><td>765,125</td><td>21.6%</td></tr>
<tr><td>2040</td><td>926,473</td><td>21.1%</td></tr>
<tr><td>2050</td><td>1,060,472</td><td>14.5%</td></tr>
<tr><td colspan="4">Raleigh, North Carolina</td></tr>
<tr><td colspan="4">NC DWR 2013</td></tr>
<tr><td>Year</td><td>Population</td><td>Appox. % Increase</td><td>50 Year % Increase</td></tr>
<tr><td>2013</td><td>489,000</td><td>-</td><td rowspan="5">150.7%</td></tr>
<tr><td>2020</td><td>683,300</td><td>39.7%</td></tr>
<tr><td>2030</td><td>844,500</td><td>23.6%</td></tr>
<tr><td>2040</td><td>995,700</td><td>17.9%</td></tr>
<tr><td>2050</td><td>1,225,700</td><td>23.1%</td></tr>
</table>

NC DWR population projection differences for Raleigh with percent increase up to 2050.

<table>
<tr><td colspan="4">Durham, North Carolina</td></tr>
<tr><td colspan="4">NC DWR 2008</td></tr>
<tr><td>Year</td><td>Population</td><td>Appox. % Increase</td><td>40 Year % Increase</td></tr>
<tr><td>2008</td><td>232,226</td><td>-</td><td rowspan="5">41.8%</td></tr>
<tr><td>2020</td><td>257,162</td><td>10.7%</td></tr>
<tr><td>2030</td><td>288,271</td><td>12.1%</td></tr>
<tr><td>2040</td><td>314,127</td><td>9.0%</td></tr>
<tr><td>2050</td><td>329,280</td><td>4.8%</td></tr>
<tr><td colspan="4">Durham, North Carolina</td></tr>
<tr><td colspan="4">NC DWR 2013</td></tr>
<tr><td>Year</td><td>Population</td><td>Appox. % Increase</td><td>50 Year % Increase</td></tr>
<tr><td>2013</td><td>262,725</td><td>-</td><td rowspan="5">58.1%</td></tr>
<tr><td>2020</td><td>286,419</td><td>9.0%</td></tr>
<tr><td>2030</td><td>329,421</td><td>15.0%</td></tr>
<tr><td>2040</td><td>372,423</td><td>13.1%</td></tr>
<tr><td>2050</td><td>415,425</td><td>11.5%</td></tr>
</table>

NC DWR population projection differences for Durham with percent increase up to 2050.

Monthly Precipitation Averages in Inches			
Month	Durham	Raleigh- Durham	Raleigh
January	3.55	3.44	3.58
February	3.41	3.26	3.43
March	4.05	3.85	3.98
April	3.37	2.88	3.11
May	3.74	3.54	3.82
June	4.2	3.57	4.13
July	4.62	4.59	4.81
August	4.53	4.45	4.61
September	3.61	3.89	4.23
October	3.09	2.99	3.15
November	3.02	3.05	3.08
December	3.26	3.09	3.33
Total	44.45	42.6	45.26

Historical monthly precipitation averages from 3 weather stations from Southeastern Regional Climate Center.

Average Temperature (C)			
	Durham	Raleigh-Durham	Raleigh
January	4.333	4.667	5.167
February	5.500	6.111	6.389
March	9.667	10.222	10.611
April	14.889	15.333	15.611
May	19.500	19.667	20.056
June	23.778	23.889	24.222
July	25.611	25.944	26.111
August	24.944	25.278	25.333
September	21.667	21.722	22.278
October	15.444	15.667	16.167
November	9.833	10.500	11.111
December	5.389	5.833	6.278

Historical monthly temperature averages from 3 weather stations from Southeastern Regional Climate Center.

Average Monthly Values		
Month	Precipitation (in.)	Temperature (°C)
January	3.523	4.722
February	3.367	6.000
March	3.960	10.167
April	3.120	15.278
May	3.700	19.741
June	3.967	23.963
July	4.673	25.889
August	4.530	25.185
September	3.910	21.889
October	3.077	15.759
November	3.050	10.481
December	3.227	5.833

Historical averages monthly precipitation and temperature from 3 weather stations from Southeastern Regional Climate Center.

Seasonal Average of Current Precipitation and Temperature		
Season	Precipitation (in.)	Temperature (°C)
Spring	10.780	15.062
Summer	13.170	18.759
Autumn	10.037	12.032
Winter	10.117	5.519

Seasonal averages for historical monthly precipitation and temperature from 3 weather stations averaged together from Southeastern Regional Climate Center.

Climate Change Scenarios (IPCC AR4)						
Season	Scenarios					
	Best Case		Mean Case		Worst Case	
	Precip.	Temp.	Precip.	Temp.	Precip.	Temp.
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
Autumn	17%	2.2°C	7%	3.5°C	-7%	5.7°C
Winter	28%	2.1°C	11%	3.8°C	2%	6.0°C

Scenarios of AR4 projections on seasonal temperature and precipitation variability (IPCC, 2007).

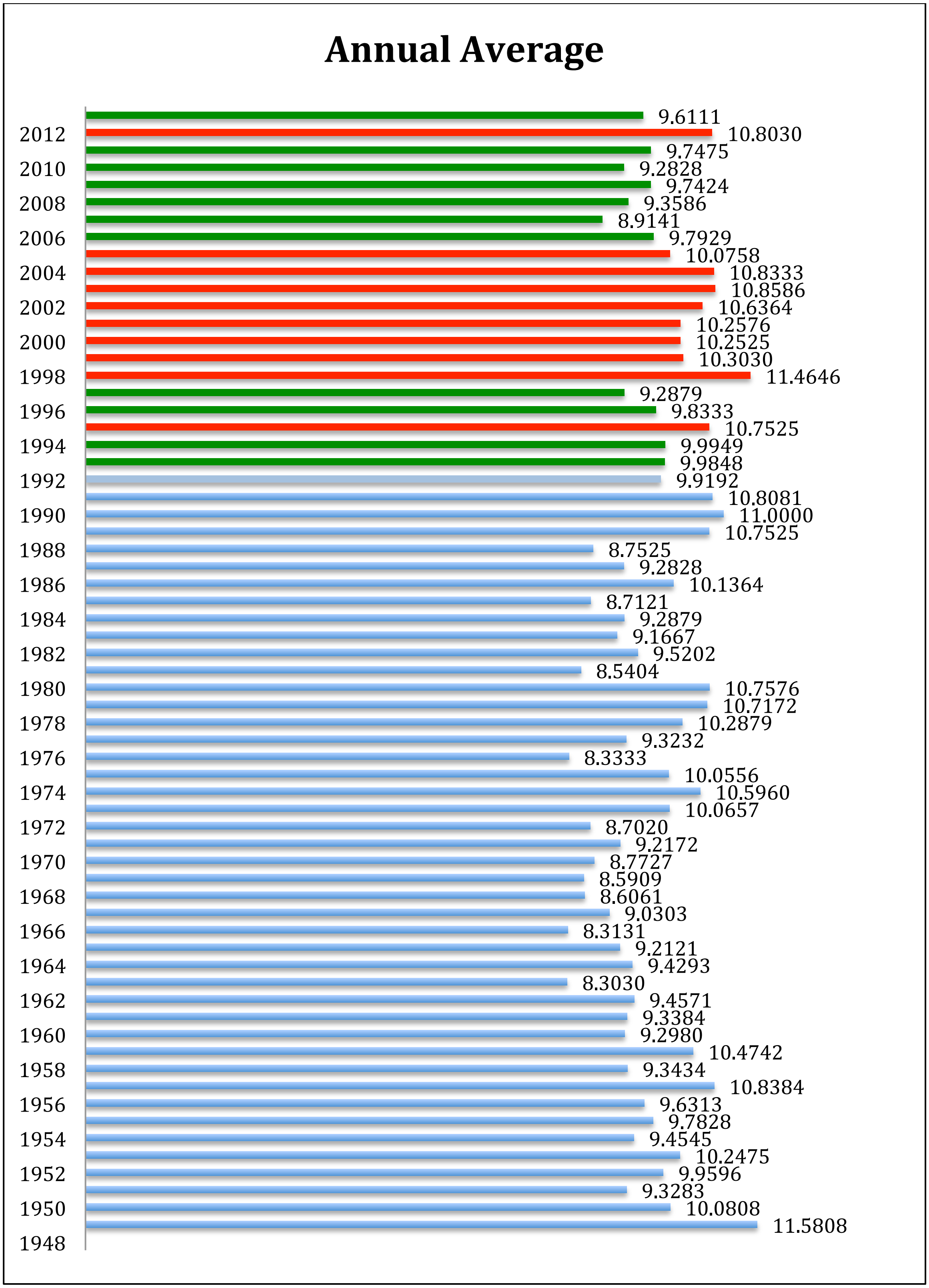
Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1948	-	-	-	-	-	-	20.22	19.28	15.28	8.33	8.61	3.00
1949	5.06	4.33	3.11	7.50	14.22	18.56	21.83	20.94	16.11	13.28	2.44	0.89
1950	6.28	0.72	-0.11	3.89	14.56	17.39	20.17	18.33	16.22	11.94	1.50	-3.50
1951	-1.06	-1.11	1.67	6.33	10.67	17.89	19.44	19.94	15.78	11.78	1.28	1.06
1952	1.39	-0.56	2.83	7.33	13.28	19.33	19.44	20.28	16.17	6.11	3.94	0.33
1953	2.83	1.00	3.56	7.17	16.11	18.50	18.72	17.94	14.00	10.00	2.89	0.61
1954	-0.44	0.50	0.94	10.56	10.83	15.83	18.33	19.11	15.61	9.44	3.28	-1.83
1955	-2.72	-0.44	3.28	8.72	12.83	14.17	20.94	21.00	18.11	9.83	1.89	-4.33
1956	-3.83	2.11	1.33	5.67	12.89	17.11	20.11	19.67	14.78	12.67	3.44	5.22
1957	0.11	3.00	2.33	9.67	14.72	19.61	18.28	18.06	18.78	8.00	6.67	1.11
1958	-4.61	-5.72	0.89	7.50	14.61	17.67	21.78	20.11	15.33	9.44	5.78	-3.61
1959	-3.00	0.06	0.94	8.83	15.11	16.78	20.94	21.06	17.44	13.17	3.89	0.06
1960	-0.28	-2.22	-4.28	8.11	12.11	17.39	19.44	20.89	17.00	10.89	3.22	-7.28
1961	-5.50	1.33	3.78	3.28	11.00	17.56	19.83	20.17	17.72	8.72	4.83	-0.94
1962	-1.00	0.89	-0.28	4.72	14.06	17.78	19.14	19.22	15.22	10.39	3.89	-3.56
1963	-2.89	-4.56	3.11	5.17	11.61	17.06	18.33	17.94	14.28	7.83	3.44	-4.94
1964	-2.44	-2.83	2.67	8.44	12.44	17.89	19.89	19.39	15.94	7.44	4.89	2.39
1965	-2.89	-1.67	0.72	6.72	14.78	16.56	19.78	19.39	17.28	7.61	3.06	-0.72
1966	-5.39	-2.00	-1.28	5.33	12.61	15.56	18.78	19.83	15.33	8.83	3.83	-0.44
1967	1.50	-3.61	3.06	7.11	11.56	16.78	19.67	20.17	14.00	9.22	-0.11	2.11
1968	-4.11	-10.22	0.22	7.11	12.11	18.00	20.61	20.33	15.00	10.61	5.00	-3.28
1969	-4.33	-3.28	-2.06	7.94	11.56	18.83	20.72	18.67	15.61	9.56	1.28	-3.78
1970	-6.67	-4.28	1.67	6.44	12.72	15.83	19.06	19.28	17.28	11.83	3.33	-1.78
1971	-4.11	-2.61	-1.72	2.89	12.06	19.50	20.28	19.83	18.44	14.61	2.22	4.33
1972	0.39	-3.94	0.39	5.83	12.44	14.17	19.44	18.78	16.22	8.78	3.22	2.61
1973	-3.06	-4.33	6.67	6.11	11.83	19.61	20.50	21.00	18.50	10.22	3.67	0.94
1974	6.28	-0.67	4.50	7.39	13.83	16.72	19.39	21.22	16.94	7.67	3.28	2.00
1975	1.67	0.67	0.94	4.11	15.44	17.00	18.78	18.89	16.94	10.89	5.28	-1.06
1976	-4.39	0.44	3.72	4.83	13.06	18.89	18.39	17.78	13.89	6.56	-1.50	-3.28
1977	-9.89	-5.44	3.89	8.83	14.28	16.89	19.56	20.50	18.39	9.83	5.72	0.17
1978	-3.94	-5.33	2.61	7.06	14.17	18.56	20.39	21.83	18.50	10.00	9.33	1.39
1979	-1.11	-3.17	5.22	8.67	15.11	17.06	19.67	20.06	18.56	10.61	7.22	0.28
1980	0.83	-2.28	2.89	9.33	15.28	17.83	21.44	20.39	19.50	10.22	2.89	-0.78
1981	-6.78	-0.50	-2.11	8.39	11.61	19.44	21.39	19.22	14.67	6.89	1.72	-2.28
1982	-5.00	0.83	3.61	3.44	13.67	18.00	20.61	18.72	15.17	9.67	6.00	4.50
1983	-2.44	-1.22	3.00	4.83	11.89	16.78	19.00	19.22	14.44	10.89	4.44	-2.50
1984	-4.44	0.78	1.00	6.50	11.56	18.00	20.00	19.89	14.00	14.44	0.44	3.94
1985	-6.50	-3.44	0.94	4.50	12.11	15.61	18.72	17.89	13.83	11.83	10.33	-4.89
1986	-4.83	2.11	1.11	5.89	12.06	17.94	20.83	19.56	17.67	11.50	7.67	0.22
1987	-3.00	-4.00	1.50	6.22	14.72	18.28	20.06	20.50	18.06	5.17	4.61	1.00

1988	-4.50	-2.78	1.89	5.61	12.61	15.56	19.72	20.83	16.50	5.89	4.94	-2.89
1989	0.06	0.50	5.06	7.33	11.56	20.11	21.28	20.28	17.61	10.44	4.06	-6.28
1990	1.67	3.22	5.44	7.89	13.83	17.50	20.17	20.33	15.67	11.78	3.50	2.89
1991	0.44	-0.56	3.94	9.72	16.67	17.94	21.83	20.56	15.83	9.94	2.56	0.50
1992	-1.33	-0.17	1.06	6.67	11.44	17.28	21.06	19.06	17.72	9.39	6.94	1.11
1993	1.44	-3.33	1.89	4.89	14.44	17.83	20.89	19.44	17.22	10.39	4.72	-0.78
1994	-3.39	-0.56	2.89	8.89	10.67	19.89	21.94	19.50	15.39	9.72	5.00	4.17
1995	-0.33	-2.89	2.94	8.44	14.94	19.61	21.94	20.94	17.44	13.11	2.11	-3.33
1996	-1.72	-1.06	-0.22	7.33	15.06	19.17	20.39	18.50	17.17	11.00	2.56	3.39
1997	-1.50	2.72	4.56	4.06	9.28	16.56	20.22	17.56	15.61	10.17	2.94	-0.33
1998	2.56	2.44	3.06	8.89	15.61	19.00	20.33	19.50	17.56	10.67	6.50	3.83
1999	1.28	0.39	-0.56	8.94	12.61	17.39	21.06	19.44	16.39	10.61	5.78	0.67
2000	-3.56	0.72	4.78	9.00	14.22	19.00	19.78	19.72	17.06	9.06	3.00	-5.56
2001	-3.28	2.11	0.67	8.11	14.17	19.83	19.11	21.17	15.39	8.72	6.83	2.33
2002	0.67	-2.33	4.72	9.72	12.39	16.94	20.33	18.83	18.11	13.39	4.22	-1.67
2003	-6.00	-0.83	5.83	9.06	14.61	18.28	21.56	22.22	16.78	10.67	7.28	-2.22
2004	-5.06	-1.83	5.44	7.72	17.28	18.78	20.56	19.50	17.61	12.83	6.33	-1.78
2005	-0.39	-0.44	1.33	5.78	10.94	18.00	21.33	21.06	16.83	11.94	4.44	-1.89
2006	2.11	-2.78	0.72	8.17	11.39	17.44	20.17	20.28	15.67	9.00	5.56	1.50
2007	-0.11	-6.56	3.11	4.78	11.78	17.39	17.89	19.78	14.78	12.89	2.33	2.56
2008	-3.11	0.06	2.06	8.72	11.94	17.44	19.39	18.44	17.17	8.78	2.06	2.50
2009	-3.22	-2.83	2.78	7.11	14.89	18.00	17.78	20.06	15.39	10.61	6.61	-1.22
2010	-4.94	-4.83	2.06	7.67	14.89	19.83	19.39	20.44	15.00	9.28	3.33	-6.22
2011	-4.17	-1.33	2.78	8.94	14.22	17.00	19.44	18.89	17.28	8.44	5.72	2.56
2012	-0.28	1.28	8.89	7.94	16.11	15.83	20.94	20.28	16.28	10.56	1.00	3.44
2013	1.06	-1.89	-2.28	8.00	12.94	18.83	21.00	19.44	15.50	11.72	1.39	2.06
2014	-6.22	-1.56	-0.78	-	-	-	-	-	-	-	-	-
Avg.	-1.91	-1.30	2.13	7.04	13.26	17.74	20.05	19.73	16.38	10.12	4.10	-0.26

Historical dew point temperatures (in degrees C) from Raleigh-Durham weather station provided by State Climate Office of North Carolina.

Season	Seasonal Average	Best Case	Mean Case	Worst Case
Spring	7.477	10.4468	7.4768	3.9506
Summer	19.173	20.9282	19.1730	16.5813
Autumn	10.198	12.5846	10.1981	7.1921
Winter	-1.158	3.4144	-1.1577	-5.6871

Seasonal dew point temperatures and associated future scenarios based on historical data.



Historical dew point temperatures. 1993-2013 served as baseline time frame for current conditions. Green bars are values lower than 10 and red bars are values higher than 10, within 1993-2013.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1948	-	-	-	-	-	-	7.7	4.8	6.6	6	7	6.4
1949	7.2	7.6	8.3	8.4	6.3	7.5	7	5.8	5.8	5.1	6.4	6.5
1950	8.8	7.2	9.3	8.7	5.3	5.3	7.6	4.3	5.5	5.3	6.8	6.5
1951	8.7	7.6	8.7	9.1	6.4	6.8	5.7	5.6	5.9	7.4	7.8	7.5
1952	8.1	8.4	8.8	8.8	7.2	6.5	6.7	6.7	6.2	5.8	6.5	6.4
1953	8.7	8.1	8.6	9.9	7.5	6.6	6.5	5.7	6.6	5.5	5.5	7.1
1954	7.3	8.6	8.6	8.5	6.8	7.4	7.4	6.7	7.5	8.1	6.7	8.1
1955	6.8	10	10.6	9.6	8.9	7.7	7.4	9	8.2	7.2	8.6	7.9
1956	9.8	9.6	10.6	11	9.8	7.6	8.3	7.4	9.1	10.6	8.7	8.4
1957	8.7	9	9.4	9.8	8.4	6.7	6.2	6.8	7	7.3	6.4	7.3
1958	7.5	9.4	8.6	8.8	5.9	6	5.8	6.2	7.3	8.3	6.9	7.2
1959	8.5	7.7	8.9	9.1	7	5.6	6.8	6.5	7.2	7.8	9.2	7.9
1960	8.9	9.1	9.1	8.1	7.9	7.5	6.3	6.4	6.2	6.3	7	7.7
1961	7.9	8.8	10.1	10.5	8.7	7.2	5.8	6.1	6.5	6.4	7.7	7.4
1962	8.2	8.5	9.1	9.3	7	7.3	6.3	6.6	7.1	7	10.6	10
1963	7.8	10.8	10.9	8.8	6.6	6	6.2	5.9	6.3	7	7.8	7.4
1964	8.6	8.9	9.8	9.6	8.7	7	7.5	7.2	7.6	6.7	7.9	8
1965	9.9	9.9	9.5	9.9	7.5	7.8	6.7	6.5	6.4	7.7	7.8	7.9
1966	10.3	9	9.7	9.7	8.9	7.6	6.9	6.3	7	7.6	8.4	8.5
1967	8.1	11.1	10	9.8	10	7.6	7.4	6.7	8.3	7	8	8.4
1968	9	9.7	11.6	9.1	9.1	8.6	8.1	8.3	6.6	7.3	9.6	9.7
1969	8.8	10.6	10.3	9.6	7.5	7.5	7.6	7.3	6.9	8.2	9.1	10.5
1970	10.3	11.3	10.8	11.5	9.4	8.5	7.6	7.6	8	8.9	8.7	10.1
1971	11	10.3	11.9	10.2	10.4	7.8	8.8	7.8	8.1	9.5	8.4	8.9
1972	8.2	10.2	9.8	9	8.7	7.9	6.8	5.5	8	8.7	10.3	10.3
1973	9.7	8.7	8.2	8	9.5	6.2	5.7	5.2	5.5	6.2	7.6	8
1974	7.1	8.3	8.5	8.3	7	6.5	6.6	4.3	6.4	5.9	7.7	7.6
1975	8	8.5	9.6	9.3	5.8	6.6	5.4	5.2	6.8	6	6.1	7.7
1976	8.8	9.1	8.6	7.7	7.9	6.6	6.4	6.8	5.1	6.5	6.5	7.3
1977	7.8	8.2	8.2	7.4	6	6.6	6.1	6.1	5.8	8	7.8	7.6
1978	8.8	7.4	8.8	8.2	6.7	6.3	5.7	5.6	5.3	6.1	5.7	6.8
1979	8.7	7.7	8.4	7.9	6.4	6.7	6.1	6.1	6.9	5.8	6.6	6.2
1980	8.6	7	9.2	7.7	6.8	8	6.7	6.4	5.3	5.8	6.8	7.8
1981	7.1	8.6	9.1	8.4	6.7	5.8	5.2	4.7	5.9	8.1	8.1	8.6
1982	8.9	8.8	8	8.5	5.9	5.9	5	4.8	5	5.8	5.2	7.2
1983	7.6	7.4	7.6	7.6	8.1	6.2	6.2	6.2	7.8	7.4	8.1	9.4
1984	7.8	8.9	9.9	8.5	8.6	7.3	7.3	6	8.4	6.3	7.4	6.6
1985	9.5	8.8	9.2	8.6	7	6.9	6.7	7.1	7.4	7.1	7.4	8.1
1986	8.5	8.1	9.4	9.5	8	8	6.7	7.5	6.3	6.7	6.9	6.6
1987	8.6	7.9	8.6	9.7	7.8	8.1	7.4	7.7	6.3	7.5	7.9	7.6

1988	7.3	8	8.7	8.4	7.6	7.6	7.5	7.6	7.2	6.8	6.8	6.9
1989	8.5	9.4	9.8	8.1	8.1	7.9	6.6	6.9	8.4	7.3	8.4	9.3
1990	8.4	9.7	8.4	8.5	9	7	7.2	5.4	5.7	6.7	6.5	7.8
1991	7.6	8	9.2	8	7	6.4	6.4	5.5	6.3	6	7.7	8.6
1992	8.9	9	9.4	9.5	8.4	6.6	7.8	6.4	6.6	7.1	7.4	8.9
1993	8.3	8.9	9.9	10.3	7.5	7.4	6.4	6.1	6.8	6.7	7.2	7.4
1994	7.5	7.6	8.8	8	8	6.3	7.1	6.4	5.9	6.6	7.5	7.4
1995	7.8	8	7.5	7.3	7.1	6.5	5.7	6.8	6.3	6.4	7.5	6.8
1996	8	6.8	8.6	8.7	6.1	5	6.3	3.8	5.7	5.6	4.3	5.6
1997	6.5	5.5	7.5	6.3	7.8	6.3	5.3	4.5	5.1	4.4	5	4.5
1998	5.7	7	7.6	7.7	5.4	5.4	5.2	5.9	4.9	3.8	5	5.3
1999	6.7	6.6	7.1	8.5	7	7.1	6	6	6.4	4.3	4.9	5.3
2000	6.7	5.8	7	8.5	7.1	7.3	5.8	5.6	5.3	3.8	4.5	6.1
2001	5.6	6.1	6.9	7.3	5.8	5.4	6	4.5	4.5	4.5	3.2	3.8
2002	4.9	7	7.3	7.2	7.2	7.2	5	6.1	5.5	5	5.6	6.1
2003	6.6	6.8	6.9	7.6	6.5	5.8	6.9	5.2	6	5.1	6	5.8
2004	6.9	6.3	7.3	7.6	7.2	5.8	4.6	5.5	6.2	4.7	4.9	6.5
2005	7.1	6.1	7.4	8.3	5.8	5.3	5.5	4.2	6.5	5.6	6.2	5.7
2006	7.1	6.9	7.3	7.1	5.8	5.5	5.7	5.6	5.1	5.1	5.2	4.5
2007	6.4	6.3	6.8	6.9	7.1	5.8	5.7	5.9	6	5	5.3	6.1
2008	6.5	7.9	8.8	7.3	7.9	6.1	5.2	4.8	6.1	4.9	5.5	6.6
2009	6.1	8.1	7.2	8	7.3	5.5	5.9	4.8	4.9	5.2	5.4	5
2010	5.7	5.5	5.9	6.2	6.7	5.6	5.8	4.7	5.8	4.9	4.2	4.6
2011	4.7	7	6.9	8.7	5	5.8	5.4	5.4	4.5	5.6	6	5.2
2012	6.6	5.7	5.8	6.3	5.2	5.4	5.2	4.7	4.3	5.1	4.6	5.9
2013	5	5.7	6	6.8	6.6	7.1	5.7	4.6	4.2	4.4	4.9	5.1
2014	6	6	7.1	7.9	-	-	-	-	-	-	-	-

Historical wind speed (in mph) from Raleigh-Durham weather station provided by State Climate Office of North Carolina.

Season	Average wind Speed
Spring	8.2
Summer	6.4
Autumn	6.5
Winter	7.7

Seasonal wind speed averages based on historical wind speed data, provided by the State Climate Office of North Carolina.

	Falls Lake Monthly Reservoir Levels											
	Monthly mean in ft (Calculation Period: 1987-05-01 -> 2013-09-30)											
YEAR	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1987	--	--	--	--	251.0	250.8	250.0	--	247.8	246.7	245.6	245.9
1988	--	250.4	250.2	--	251.1	250.6	--	--	--	247.1	248.9	248.4
1989	248.0	251.4	--	--	--	--	251.4	249.1	247.4	248.7	245.6	247.5
1990	247.1	242.2	249.1	251.4	251.7	250.1	249.3	249.5	248.8	248.0	249.4	250.0
1991	251.5	250.2	250.6	250.8	250.9	250.5	--	248.5	247.4	246.9	245.8	245.3
1992	--	250.1	250.6	--	--	--	250.9	250.0	--	248.6	249.2	250.3
1993	251.1	250.3	--	252.2	251.1	250.7	249.3	247.7	--	244.1	--	245.0
1994	248.5	250.6	251.7	251.2	250.8	250.0	249.4	249.6	248.9	248.1	247.8	247.5
1995	249.1	251.2	251.3	250.4	250.0	251.3	252.2	250.4	250.0	251.2	251.0	250.6
1996	250.8	250.6	250.6	250.9	251.2	251.2	250.7	251.1	257.0	251.0	250.6	251.0
1997	250.4	251.3	--	250.8	251.9	251.2	250.8	250.5	249.4	248.5	248.5	249.0
1998	252.6	259.3	256.9	252.8	251.2	251.3	--	249.5	249.0	247.8	246.7	246.6
1999	250.7	250.5	250.8	251.2	251.3	250.2	249.3	247.7	255.7	259.6	252.1	252.1
2000	252.2	253.5	252.2	252.2	252.1	251.9	252.4	251.8	251.4	251.0	250.1	249.9
2001	249.8	250.3	252.7	255.5	251.2	251.6	251.1	251.7	250.9	249.8	248.4	247.7
2002	248.4	250.6	251.0	251.8	250.8	249.2	247.3	245.5	245.3	249.7	252.5	253.4
2003	252.0	252.8	256.8	258.7	253.1	252.0	252.2	252.5	252.1	251.3	251.2	252.2
2004	251.6	252.2	251.8	252.3	252.0	251.4	250.8	251.8	252.1	251.6	251.9	252.3
2005	252.1	251.7	252.0	251.7	251.3	251.1	250.1	249.0	247.0	245.2	243.6	246.4
2006	249.1	250.4	250.7	250.7	251.5	252.8	251.9	250.7	251.0	250.8	254.0	253.2
2007	252.7	251.8	252.2	252.4	251.6	250.8	249.4	247.7	245.5	243.6	242.8	241.9
2008	243.0	243.4	248.1	251.9	252.2	251.3	251.5	250.5	254.4	252.0	251.4	252.6
2009	252.1	252.3	254.0	252.9	251.7	251.9	250.7	249.6	248.5	247.9	250.8	254.8
2010	253.0	257.0	252.2	252.0	252.2	252.2	251.1	250.6	249.3	249.8	249.2	248.9
2011	248.9	249.4	250.2	252.6	252.3	251.8	250.7	249.3	248.5	247.7	247.7	247.9
2012	248.6	249.0	251.3	--	252.5	251.7	250.8	250.4	251.0	251.5	250.9	250.6
2013	252.1	252.2	252.1	252.0	252.2	252.9	252.8	251.8	251.5	--	--	--
Mean of monthly Gage height	250.2	251.0	251.7	252.2	251.6	251.2	250.7	249.9	250.0	249.2	249.0	249.3

Historical lake levels of Falls Lake in feet. Provided by USGS.

YEAR	Jordan Lake Monthly Reservoir Height											
	Monthly mean in ft (Calculation Period: 1995-11-01 -> 2013-09-30)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1995											217.6	216.5
1996	217.2	217.6	216.9	216.3	216.3	216.2	215.5	216.3	224.1	216.7	216.4	216.7
1997	217.2	217.7	216.8	217.3	218.3	216.5	216.5	215.9	214.8	214.1	214.7	216.7
1998	220.0	223.7	221.4	217.3	216.9	216.3	215.4	214.4	213.9	212.5	211.1	211.2
1999	217.4	216.9	216.8	216.6	216.7	215.3	214.5	213.2	218.4	218.4	216.7	216.6
2000	217.2	221.3	218.4	217.2	216.5	216.6	217.1	216.5	217.3	215.5	213.8	213.4
2001	213.8	215.8	217.4	217.8	216.3	216.8	216.1	216.3	216.2	214.7	212.7	
2002	213.1	216.8	216.7	216.6		212.7	211.0	210.3	213.7	217.3	217.5	218.1
2003	216.5	217.9	221.2	224.1	217.5	217.2	216.9	217.3	216.8	216.5	216.3	216.6
2004	216.3	217.1	216.3	216.6	216.8	216.6	216.6	216.5	216.8	216.5	216.7	217.5
2005	217.3	216.8	217.2	216.7	216.3	216.1	215.8	216.1	214.1	213.0	212.5	216.7
2006	216.6	216.9	217.1	217.2	217.0	217.3	217.0	216.1	216.7	216.6		217.4
2007	217.3	216.8	217.4	218.1	216.6	216.0	215.2	213.8	211.9	210.9	212.2	211.7
2008	214.3	216.2		218.6	218.4	216.1	216.1	215.1	218.0	216.6	216.1	217.5
2009	217.2	216.8	218.9	217.4	216.7	217.2	215.1	214.0	212.8	212.8	216.8	219.1
2010	218.1	221.4	216.8	216.8	216.7	216.6	215.7	216.1	214.9	216.8	216.3	216.0
2011	216.5		217.0	216.9	216.5	216.0	215.8	214.3	213.4	214.2	216.6	216.9
2012	216.7	216.8	217.4	216.6	216.7	216.4	215.5	216.1	216.4	216.2	214.8	213.9
2013	216.5	216.7	216.7	216.4	216.7	217.4	218.5	216.2	215.8			
Mean of monthly Gage height	216.6	217.8	217.7	217.5	216.9	216.3	215.8	215.3	215.9	215.3	215.2	216.0

Historical lake levels of Jordan Lake in feet. Provided by USGS.

Lake Michie

00065, Gage height, feet,

Monthly mean in ft (Calculation Period: 1987-12-01 -> 2013-09-30)

YEAR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987												0.5
1988	2.0	1.8	1.5	1.6	1.3	1.3	0.4		0.6	0.5	1.1	1.3
1989	1.4	2.5	3.9	2.7	2.4		2.3	1.7	1.1	1.7	1.5	2.1
1990	2.7	3.0	2.1	2.6	2.5	1.6	1.0	0.5	0.4			
1992										1.1	1.8	1.9
1993	2.9	2.1	3.9	3.3	1.4	0.9	1.1	0.5	0.5			
1999										3.7	1.5	
2000			2.3	3.0	1.7	1.5	1.3	1.2	1.1	1.2	1.1	
2001				2.1						0.4	0.4	0.4
2002	0.4	0.4	0.8	0.6	0.4	0.4	0.4	0.4	0.4	1.9	2.2	2.8
2003	1.7	2.9	3.7	4.4	2.7		2.2	1.6	1.8	1.3	1.4	2.2
2004			1.5	1.8	1.3	0.5	0.4	1.7		1.2	1.8	2.0
2005		2.0		1.8	1.4	1.0	0.4	0.4	0.4	0.4	0.5	1.3
2006	1.4	1.1	0.8	0.9	1.1		1.1	0.4	0.8	1.1	2.4	1.6
2007	2.2	1.8	2.1	2.1	1.3	0.6	0.4	0.4	0.4	0.5	0.4	0.4
2008	0.4	0.5	1.4	2.1	1.0	0.4	0.4	0.5	2.1	1.0	1.3	2.2
2009	2.1	1.5	2.9	2.0	1.4	2.1	0.9	0.5	0.6	0.6	2.3	
2010		3.3	2.1	1.5	1.5	1.0	0.6	0.6	0.5	0.7	0.5	0.5
2011	0.5	0.5	1.8	1.6	1.4	0.4	0.4	0.4	0.5	0.4	0.5	0.8
2012	0.7	1.1	1.6	1.1	1.5	0.7	0.4	0.4	0.8	0.5	0.4	0.7
2013	1.9	2.1	1.9	1.9	1.6	1.8	2.3	1.2	0.5			
Mean of Monthly Gage Height	1.6	1.8	2.2	2.1	1.5	1.0	0.9	0.8	0.8	1.1	1.2	1.4

Historical lake levels of Lake Michie in feet. Provided by USGS.

Little River Lake												
00065, Gage height, feet,												
Monthly mean in ft (Calculation Period: 1995-11-01 -> 2002-09-30)												
YEAR	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1995											2.1	2.4
1996	2.0	2.5	2.6	2.2	2.1	1.4	1.3	1.6		2.1	2.4	3.1
1997	3.0	3.2	3.0	2.8	2.0	1.9	1.6	1.6	1.6	1.6	1.7	1.7
1998		3.5	3.6	2.6	1.6	1.2	1.1	1.1	1.2			
1999		1.8	1.9	2.0	1.5	1.2	1.2	1.6	2.9	1.8	2.0	1.9
2000	2.2	3.0	2.5	2.9	1.7	1.3	1.3	1.3	1.3	1.8		2.1
2001	2.3	2.4	2.8	2.3	1.6	1.4	1.7	1.6	2.3	1.8	2.2	
2002		1.2	1.3	1.5	1.4		1.2	1.2	1.1			
Mean of Monthly Gage Height	2.4	2.5	2.5	2.3	1.7	1.4	1.3	1.4	1.7	1.8	2.1	2.3

Historical lake levels of Little River Lake in feet. Provided by USGS.

Seasonal Average	Falls Lake	Jordan Lake	Lake Michie	Little River Lake
Spring	251.833	217.367	1.913	2.183
Summer	250.6	215.8	0.9167	1.377
Autumn	249.4	215.467	1.0233	1.87
Winter	250.167	216.8	1.57	2.39

Average seasonal reservoir levels for each reservoir.

YEAR	**Falls Lake Monthly Average Temperature**											
	Monthly mean in deg C (Calculation Period: 2009-10-01 -> 2013-10-31)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
2009										19.9	14.5	8.7
2010		5.1	10.9	20.3	24.4		31.4	30.7	27.5	21.7	15.7	8.1
2011	4.8		12.8	17.2	24.1	29.9	31.2					11.8
2012	9.2	9.8	16.0		25.4	28.4	31.3	29.6	26.9	21.3	13.7	10.9
2013	8.5	8.0	10.7	17.9	22.4	27.5	29.6	29.1	27.1	21.4		
Mean of monthly Temperature, water	7.5	7.6	12.6	18.5	24.1	28.6	30.9	29.8	27.2	21.1	14.6	9.8

Historical Monthly Temperatures for Falls Lake. These temperatures were used for the other lake because that data was not available. Provided by USGS.

Seasonal Average	Temp. (Deg C)
Spring	18.4
Summer	29.77
Autumn	20.91
Winter	8.3

Seasonal water temperatures used for each lake, based off of Falls Lake data. Provided by USGS.

Water and Air Temperature Correlations by Season		
Season	Linear Equation	R-squared Value
Spring	$y= 1.0796x + 0.7698$	$R^2 = 0.93067$
Summer	$y= 0.73x + 0.89041$	$R^2 = 0.89041$
Autumn	$y= 0.979x + 5.1043$	$R^2 = 0.95774$
Winter	$y= 0.6472x + 4.6477$	$R^2= 0.67322$

Relation of air temperature and water temperature by season. Equation is used to predict future water temperature.

Season	Current Evaporation in Inches
Spring	0.203
Summer	0.337
Autumn	0.214
Winter	0.096

Current evaporation rate of Lakes in the Triangle, based on water temperature, dew point temperature, and wind speed.

Best Case					
	Precipitation	Net Change from Normal	Evaporation	Net Change from Normal	Change in Storage (ΔS)
Spring	13.26	2.48	0.197	-0.006	2.486
Summer	14.882	1.712	0.342	0.005	1.707
Autumn	11.743	1.706	0.238	0.024	1.682
Winter	12.949	2.832	0.076	-0.02	2.852
Mean Case					
	Precipitation	Net Change from Normal	Evaporation	Net Change from Normal	
Spring	12.07	1.29	0.275	0.072	1.218
Summer	13.302	0.132	0.425	0.088	0.044
Autumn	10.74	0.705	0.315	0.101	0.604
Winter	11.22	1.103	0.134	0.038	1.065
Worst Case					
	Precipitation	Net Change from Normal	Evaporation	Net Change from Normal	
Spring	10.35	-0.43	0.3996	0.1966	-0.6266
Summer	10.931	-2.239	0.555	0.218	-2.457
Autumn	9.334	-0.703	0.428	0.214	-0.917
Winter	10.32	0.203	0.191	0.095	0.108

Change in precipitation and evaporation from current conditions based on IPCC scenarios of climate change.

Total Raleigh Supply Change			
Season	Best Case	Mean Case	Worst Case
Spring	+9.1	+4.5	-2.3
Summer	+6.3	+0.2	-9.0
Autumn	+6.2	+2.2	-3.4
Winter	+10.7	+4.0	+0.4

Total change to Raleigh’s water supply in millions of gallons per day for each season of each climate change scenario.

Total Durham Supply Change			
Season	Best Case	Mean Case	Worst Case
Spring	+1.800	+0.880	+-0.460
Summer	+1.220	+0.040	+-1.744
Autumn	+1.210	+0.350	+-0.658
Winter	+2.110	+0.790	+0.090

Total change to Durham’s water supply in millions of gallons per day for each season of each climate change scenario.

160 Acre Well Spacing in Sanford Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
17	17.00	28.34	2.43
Water needed	None	None	None
160 Acre Well Spacing in Durham Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
47	47.00	78.35	6.71
Water Needed	23.5	39.2	3.355

Best-case fracking scenario with large well spacing and lower water requirements from Raleigh and Durham.

160 Acre Well Spacing in Sanford Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
27	27.00	45.01	3.86
Water Needed	6.8	11.3	0.965
100 Acre Well Spacing in Durham Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
75	75.00	125.03	10.71
Water Needed	56.3	93.8	8.0

Mean-case fracking scenario with medium well spacing and medium water requirements from Raleigh and Durham.

40 Acre Well Spacing in Sanford Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
68	68.00	113.36	9.71
Water Needed	34.0	56.7	4.9
40 Acre Well Spacing in Durham Sub-basin			
Number of Wells	1 MGD	1.667 MGD	142857 g/d
189	189.00	315.06	27.00
Water Needed	189.00	315.06	27.00

Worst-Case fracking scenario with small well spacing and higher water requirements from Raleigh and Durham.

APPENDIX B: SAMPLE CALCULATIONS

Finding the Saturation Vapor pressure of the Water:

$$e_0 = 6.11 \times 10^{\frac{(7.5 \times T)}{(237.3+T)}}$$

Water temperature: Spring, 18.4°C (under current conditions)

$$e_0 = 6.11 \times 10^{\frac{(7.5 \times T)}{(237.3+T)}}$$

$$e_0 = 6.11 \times 10^{\frac{(7.5 \times 18.4)}{(237.3+18.4)}}$$

$$e_0 = 6.11 \times 10^{\frac{(138)}{(255.7)}}$$

e_0 = 21.17millibars

e_0 = 21.17 mb X 0.02953 (to convert to inches of HG (Mercury)).

$$e_0 = 0.63\ inches\ of\ Hg$$

This is the same process for finding actual vapor pressure, $e_a = 6.11 \times 10^{\frac{(7.5 \times T_d)}{(237.3+T_d)}}$, however, dew point temperature is used instead of water temperature.

Calculating the Evaporation of the Lake

$$E = C\,(e_0 - e_a)\left(1 + \frac{W}{10}\right)$$

Ex: Spring (under current conditions

e_0 =0.63 in of Hg

e_a =0.32 in of Hg

W = 8.2 mgh

$C = 0.36$

$$E = C\,(e_0 - e_a)\left(1 + \frac{W}{10}\right)$$

$$\square = (0.36)\,(0.63 - 0.32)\left(1 + \frac{8.2}{10}\right)$$

$E = 0.203$

The current spring evaporation value is 0.203 inches

Converting Change in Storage Value into Millions of Gallons per Day

Best-case climate change impact on Falls Lake in spring

Net Change from current conditions: $\Delta S = P - E$

P= +2.48 inches net gain of precipitation

E=-0.006 inches net gain in evaporation (there are less 0.006 inches of water evaporated in this scenario compared to baseline conditions.

$\Delta S = P - E$

$\Delta S = 2.48 - (-0.006)$

$\Delta S =$ 2.486 inches (0.207 ft)

Falls Lake Surface Area= 12410 acres

12410 acres X 0.207 ft = 2,568.87 acre ft

There are 0.326 million gallons of water in 1 acre ft

2,568.87 acre ft X 0.326 Mgal = 837.45 million gallons of water

There are 92 days in the season of spring

837.45 Mgal / 92 days = 9.1 Mgal/day

In the spring, under the best case climate change scenario, water supply in the Falls Lake will increase by 9.1 million gallons a day compared to current conditions.