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# Modeling the Impacts of Climate Change, Landuse Change, and Human Population Dynamics on Water Availability and Demands in the Southeastern U.S.

**Ge Sun, Research Hydrologist, ge_sun@ncsu.edu**

**Steven G. McNulty, Research Ecologist and Program Manager, steve_mcNulty@ncsu.edu**

**Erika Cohen, Resource Information Specialist, erika_cohen@ncsu.edu**

**Jennifer Moore Myers, Resource Information Specialist, jennifer_mooremyers@ncsu.edu**

Southern Global Change Program, USDA Forest Service, Raleigh, NC 27606

**David Wear, Project Leader, dwear@fs.fed.us**

Economics of Forest Management and Protection, USDA Forest Service, RTP, NC 27709

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***Abstract.*** The objective of this study is to develop a method to fully budget annual water supply (Precipitation – Evapotranspiration (ET) + Groundwater supply + Return Flow) and water use from thermoelectric, irrigation, domestic, industry, livestock, mining, and commercial uses at the regional scale. We used a generalized annual ET model that estimates water loss as a function of potential ET, annual precipitation, land cover type, and topography. The Water Supply Stress Index (WSSI), the ratio of water demand and supply was developed to evaluate water stress conditions. The Water Supply Stress Index Ratio (WSSIR) was developed to quantify the impact of future changes in climate, land use, and population individually or in combination on WSSI. Modeling results from two Global Circulation Models (GCMs) (Hadley and CGC1), one land use change model, and one population change model were integrated to project future water supply and use over the next 25 years. We found that climate will have the largest impact on water stress, followed by population, and finally land use change across the southeastern U.S. during this period.

**Keywords.** Climate change, water availability, water demand, landuse change, regional modeling

## Introduction

Water is essential to the success of agriculture and industry, and public well being. Water resources across the United States have been increasingly stressed over the past decades, mainly due to population growth and climate change and variability (Gleick, 2003). A partial survey by the U.S. General Accounting Office revealed that many States, both in the west (e.g., Colorado) and east (e.g., South Carolina), were expecting significant local or regional water shortages. Water availability and use at the national or local levels is not available since a comprehensive assessment has not been done for 25 years (U.S. General Accounting Office, 2003). The National Research Council (2002) warned that this lack of water resources information may have severe economic and environmental consequences. The National Science and Technology Council Water Availability and Quality Subcommittee (2004) released a report that emphasized the urgent needs for developing science and tools to precisely quantify current and future water demands from human and nature and water availability at multiple scales. Recent national-scale dialogs conclude that integrated assessment of water resources is an important step toward preventing future water crises.

The southeast has the fastest population growth rates in the U.S., and this trend is expected to continue well into the 21st century. In addition to an increasing population base, general circulation models (GCMs) predict that the southern U.S. will experience significant increases in air temperature and variability of precipitation associated with global warming (Kittel et al., 1997). Climate change will affect many aspects of natural ecosystems, as well as the regional economy. For example, in irrigated areas, thus water withdrawal, will be expected to increase when water loss through evapotranspiration becomes higher (Peterson et al., 1990; Doll, 2002). In addition to climate and population changes, the Southern Forest Resource Assessment concluded that land use patterns have and will continue to change dramatically over the next 20 to 40 years (Wear and Greis, 2002). For example, although the total area of forest land did not change greatly, large areas of land have been lost to urban uses (e.g. Florida, Piedmont of North Carolina), while agricultural areas in the lower Gulf coastal plains have been reforested (Wear and Greis, 2002). The combination of these factors may predispose the southern U.S. to water shortages in the coming decades.

However, the modeling tools needed to assess and project the water availability and use are lacking at the regional level. Individually, hydrologic models, GCM predictions of climate change, demographic models of population change, and land use change models have been developed (McNulty et al., 1998; Arnold et al., 1999; Wear and Greis, 2002; Sun et al., 2005;). Unfortunately, these individual models are designed to work at different spatial scales and are not meant to interact in a manner necessary for assessing potential water resource stress at the regional scale. As illustrated in Figure 1, key drivers for both water availability and use are closely linked, and their interactions are more complex then their individual processes. Most of the existing regional scale water resource assessments have treated water supply and water withdrawals separately. Few studies have addressed the combined trend of the two variables. For example, Arnold et al. (1999) mapped the water balance for the continental U.S. using the HUMUS hydrologic model, and later the model was applied to examine how global climate including atmospheric $CO_2$ and El Nino/Southern Oscillation impact water yield (Thomas et al., 2003). Using historical USGS water use data, Brown (2000) projected fresh water withdrawals for the next 40 years for five economic sectors including livestock, domestic and public, industrial and commercial, thermoelectric, and irrigation.

This study explores an integrated modeling approach that combines an annual water yield model with climate, land use/land cover, and population change projections to assess water

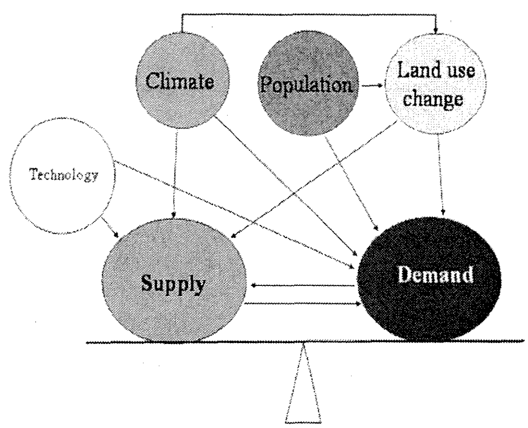



Figure 1. Factors affecting water supply and demand and their relations.

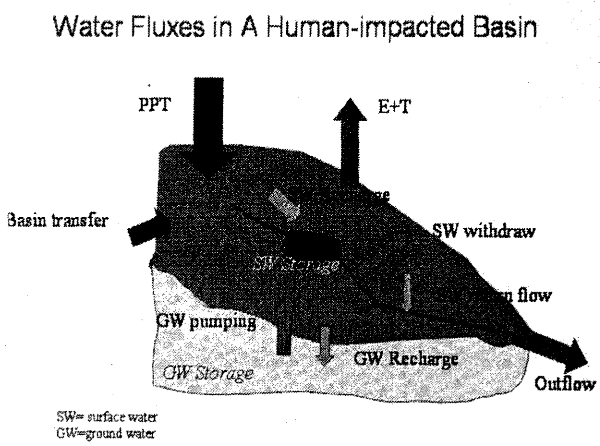



Figure 2. Sketch of water fluxes in a human-impacted basin.

## Methods

The guide for a full accounting of both water supply and water use was the watershed budget of a basin, as illustrated in Figure 2. In our study, we used the USGS Hydrologic Unit Code (HUC) as the working scale. There are 666 eight-digit HUCs in the southern U.S., covering 13 states from Virginia to Texas. Databases described below included historic water use compiled by the USGS, historical and projected climate, population, and land use. All databases were scaled to the HUC level. Once databases were assembled, alternative scenarios were developed to individually and collectively quantify the impacts of climate, population and land use changes on water availability and demand and water stress.

### *Databases*

#### Historic and Projected Climate Data

Historic climate data compiled by the VEMAP group (Kittel et al., 1997) were used as the baseline climate to which the climate change scenarios were compared. The climate data were in a gridded 0.5° by 0.5° (about 50 km * 75 km) format for the continental US. We subset the data from 1950 to 1990 that corresponded to the 13 southern US states and overlaid the climate data with the 666 corresponding southern USHUCs. These air temperature and precipitation data drive the water model that is described later.

Two future climatic scenarios were acquired from predictions by the HadCM2Sul model developed at the UK Hadley Climate Research Center, and the CGC1 model developed by the Canadian Climate Centre (CGC1), representing warm and wet and hot and dry scenarios, respectively. Both are transient global climate models. When compared to the average historical climate (1985-1993), the HadCM2Sul GCM suggests that the region east of the Mississippi River is projected to experience an increase in annual precipitation of up to 20% with somewhat increases air temperature, but a decrease of precipitation by 10% and a large rise of air temperature (>0.5) west of the Mississippi River by 2025. In contrast, the CGC1 model predicts most of the southern U.S. will have a 10% decrease in precipitation and large increases of air temperature of 1-2 °C by 2025 (Fig. 3).

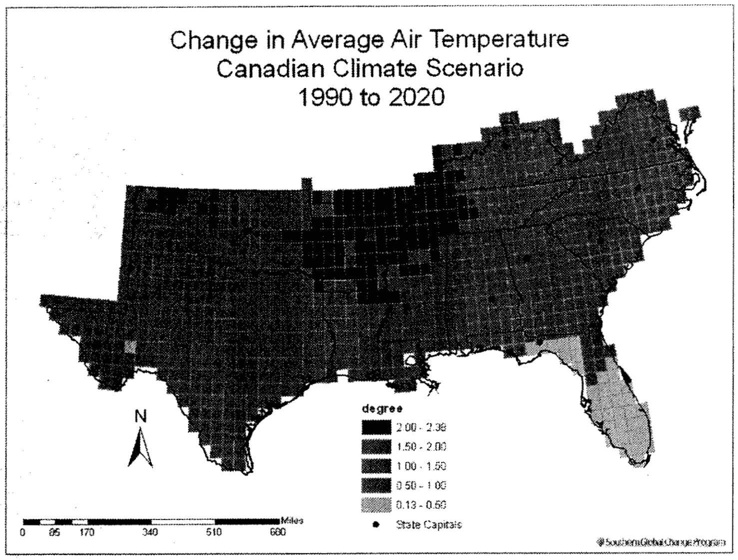
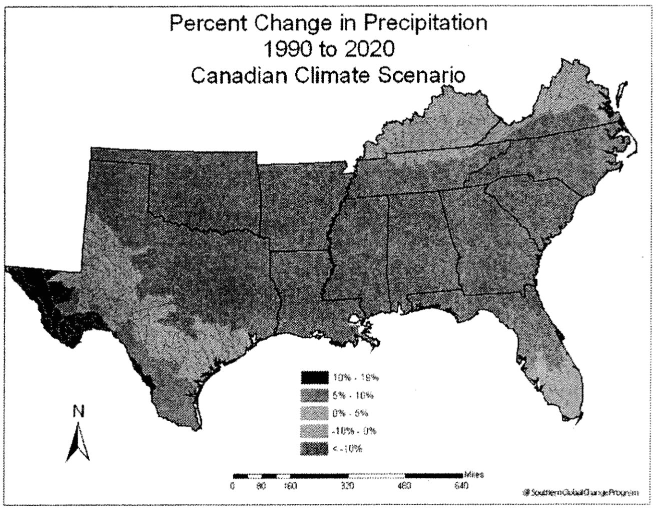



Figure 3. Predicted climate change across the Southern U.S. by the CGC1 model over the next 20 years.




## Historical and Projected Land Use/Land Cover Data

Land cover data were used to drive the water yield model thus for estimating the water supply term. Land use data for irrigated areas was used for estimating water use by the irrigation sector, a major water user. The 1992 MRLC remote sensing land use/land cover dataset (http://edc.usgs.gov/glis/hyper/guide/mrlc) was used to calculate the percentage of each vegetation type within each modeling unit (8-digit HUCs). Land cover was aggregated into five classes including evergreen forest, deciduous forest, crop, urban, and water. Future land cover composition was projected via land use changes in forest, agriculture, urban, and other lands by an economic model (Wear and Greis, 2002). It was projected that the South will lose 12 million or 8% of the current forest land base to development, and about 10 million agricultural land will be converted to forest in the next 25 years (Wear and Greis, 2002).

## Historical and Projected Population Data

According to 1990 U.S. Census Bureau records, about 100 million people lived in the 13 southern states (US Census, 2002). Population projections at the census block level are available to 2050 from NPA Data Services. We aggregated their data to the 8-digit HUC level for each year between 2000 and 2030, and then averaged estimates from 2020 to 2030 were used as the mean for 2025. Between 1990 and 2025, the population of the 13 southern states was predicted to increase by more than 50% (NPA Data Services Inc., 1999). No new areas of growth within the region were projected, but current urban centers are expected to expand, and rural areas are generally expected to become more densely populated. However, population growth by 2025 will not be uniform, varying from -21% to +508% in the region when compared to 1990 levels (Fig. 4).

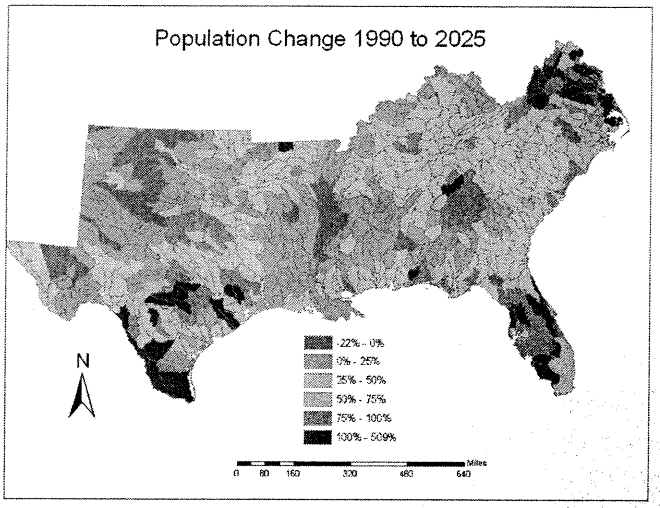



Figure 4. Projected population change in the southern US in the next 25 years (NPA Data Services).

### *Algorithms for Estimating Water Availability, Water Use, and Water Stress*

We define water availability as the total potential water available for withdraw in a basin expressed in the following formula:

$$WS = P - ET + GS + \sum RF_i$$

Where WS = Water supply in million gallons; P = Precipitation; ET= Watershed evapotranspiration calculated by an empirical formula as a function of potential evapotranspiration, precipitation, and land cover types. Detailed methods are found in Sun et al. (2005);

GS = deep groundwater supply, with historical groundwater withdrawal representing groundwater availability;

RF = Return flow from each of seven water users *i* including domestic, irrigation, thermoelectric, industrial mining, and livestock sectors. RF is calculated as the historical return flow rate (RFR) multiplied by the water use (WU.);

And where water demand (WD) represents the sum of all water use (WU) by each of the seven sectors: $WD = \sum WU_i \quad i= 1\text{-}7 \qquad (1)$

Water demand for domestic water use was predicted by the following model that was derived by correlating USGS historical water use (million gallons per day) in the domestic sector and the population (in thousand persons) for the years 1990 and 1995 at the HUC level.

WU in the domestic sector = 0.008706 Population + 1.34597 $R^2 = 0.514$, n=666 (2)

Similarly, water demand for irrigation water use was predicted by the following model that was derived by correlating USGS historical water use (million gallons per day) in the irrigation sector and the irrigation area (in thousand acres) for the years 1990 and 1995 at the HUC level.

WU by Irrigation = 1.3714 Irrigation Area + 2.06969 $R^2 = 0.666$, n = 666 (3)

Currently, we do not have water use models for other five sectors, so we used the historical water use data for future periods. We plan to develop similar empirical models for these five sectors using economical variables as the methods developed in Brown (2000).

We proposed a Water Supply Stress Index (WSSI) (Equation 4) and Water Supply Stress Index Ratio (WSSIR) (Equation 2). The WSSI was used to quantitatively assess relative magnitude in water supply and demand at the 8-digit HUC level. The WSSIR was used to assess the relative change in the WSSI between the baseline scenario (x = 1) and one of the other scenarios (x = 2 through 6) as described later. Positive WSSIR values indicate increased water stress and negatives indicate reduced water stress when compared to those of the historical conditions (Scenario 1):

$$WSSI_x = \frac{WD_x}{WS_x} \quad (4) \qquad \text{and} \qquad WSSIR_x = \frac{WSSI_x - WSS_1}{WSSI_1} \quad (5)$$

Where x represents simulation scenarios described below.

### *Simulation Scenarios*

Six scenarios were developed to examine historic and future water stress resulting from projected changes in climate, population, and land use (Table 1). Scenario 1 represents the average historic (i.e., 1985-1993) climate, population distribution, and land cover conditions across the 13 southern states. Calculations of water availability and water demand will serve as the baseline for comparisons with alternative climate, population, and land cover conditions. Scenario 2 represents predicted changes in climate by the Hadley2 and CGC1 GCMs on water availability, water demand, and stress indices (WSSI and WSSIR) by 2020 and assumes no population or land use change. Similarly, Scenario 3 examines the impacts of predicted changes in human population by 2020 and assumes no climate or land use changes. Scenario 4 was designed to examine impacts of land use change. As illustrated in Figure 1, land use change will affect the water availability (water balance) and water use (demand for irrigation). Scenario 5 was designed to examine the combined effects of future climate and population changes (Table 1) while Scenario 6 was designed to study the combined consequences of climate, population, and land use changes in the next 20 years.

## Results

### *Historic Water Supply Stress (Scenario 1)*

The amounts of precipitation and air temperature are the most important determinants of water loss by evapotranspiration and thus water yield across the southern US (Lu et al., 2003). Historically, precipitation and air temperature have a wide range of variation across the region: central Texas averages less than 70 cm of precipitation per year while parts of the Gulf coast and southern Appalachians receive almost 200 cm. Average annual air temperature is roughly inversely proportional to latitude within the region. Therefore, the Appalachians and the Gulf coasts had the highest water availability, while the lowest was found in semi-arid western Texas. Irrigation and thermoelectric sectors were the two largest water users followed by domestic-livestock and industrial users. Consequently, the western Texas region had the highest WSSI, or the highest water supply stress (Fig. 5). Identified stressed areas also included southern Florida, southern Georgia, and the Mississippi valley areas that depend on irrigated agriculture. Several isolated HUCs in high precipitation regions east of the Mississippi River also showed high water stress, primarily due to thermoelectric water use.

Table 1. Modeling Scenarios as Combinations of Climate, Vegetation and Population

| Scenario and Land Cover | Land cover | Climate | Population |
|---|---|---|---|
| Scenario 1: (Baseline) | 1992 MRLC land cover | Historic Data (1985-1993) | 1990 Census |
| Scenario 2: (Climate Change) | As in Scenario 1 | Projected by two GCMs (HadCM2Sul and CGC1) | As Scenario 1 |
| Scenario 3: (Population Change) | As in Scenario 1 | As in Scenario 1 | Projected to 2020 |
| Scenario 4: (Land use Change) | Projected to 2020 | As in Scenario 1 | As in Scenario 1 |
| Scenario 5: (Climate + Population Change) | As in Scenario 1 | As in Scenario 2 | As in Scenario 3 |
| Scenario 6: (climate + population + land use change) | As in Scenario 4 | As in Scenario 2 | As in Scenario 3 |

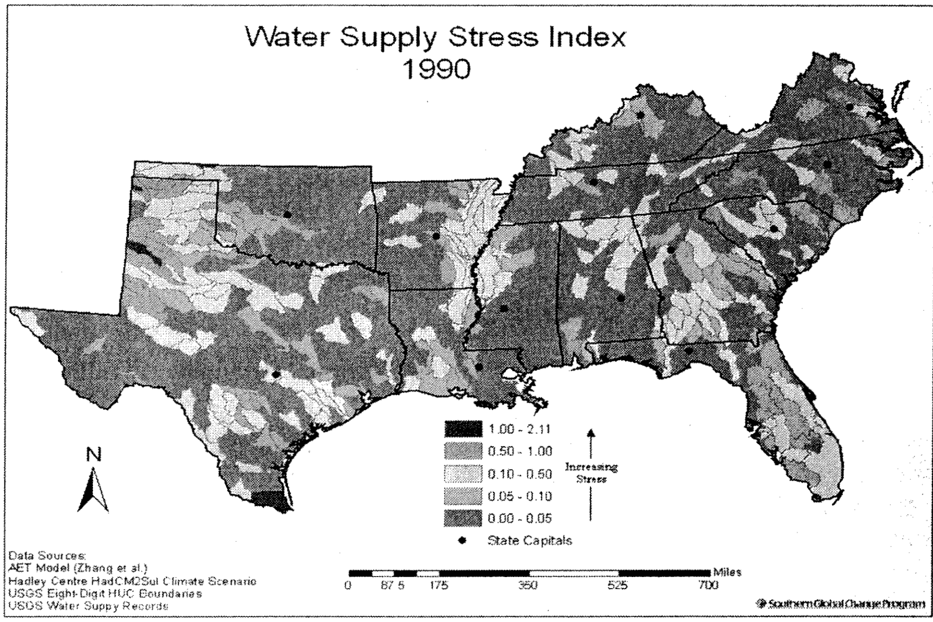



Figure 5. Modeled historical (1985-1993) Water Supply Stress Index (WSSI).

## *Climate Change Impact (Scenario 2)*

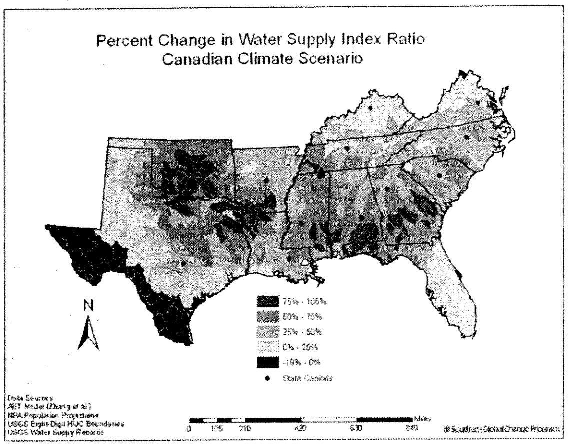



Figure 6. Modeled impact of climate change (CGC1 GCM ) on Water Supply Stress Index (WSSI) showing increased water stress across the southern U.S. in the next 25 years.

Compared to the historical hydrologic conditions (1985-1993), water yield in 2020, as calculated as the differences between annual precipitation and actual evapotranspiration, was projected to have a large decreasing trend with the CGC1 scenario, due to a large increase in air temperature and moderate decrease in precipitation, but an large increasing trend withthe HadCM2Sul due to large increases in precipitation and moderate increases in air temperature across the study region. The contrasts between the two scenarios are most pronounced in areas with high runoff in the piedmont and mountain regions. As a result, changes of the WSSI values (i.e., WSSIR) will increase up to 105% if the CGC1 GCM scenario occurs (Fig 6.) across the study region, but they may be reduced east of the Mississippi valley under the HadCM2Sul GCM prediction.

## *Population Change Impact (Scenario 3)*

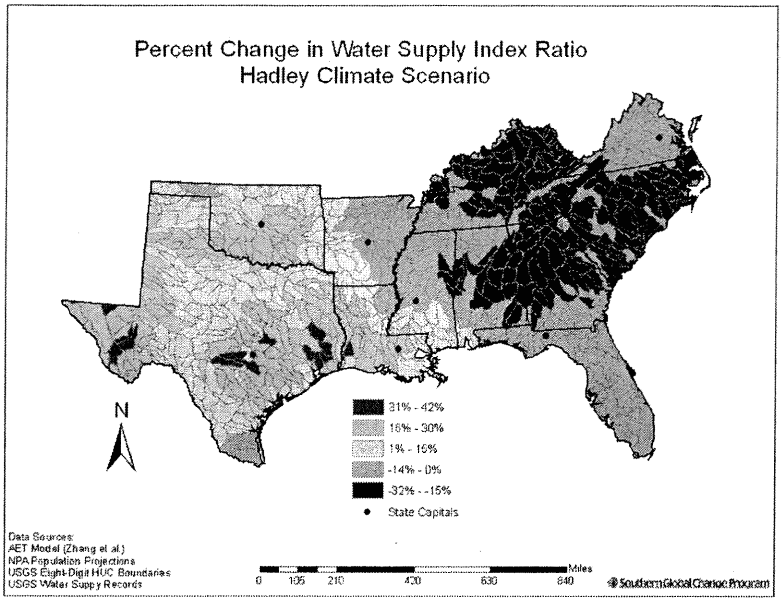
The amount of water demand by the domestic water use sector is directly related to population, as demonstrated in Equation 2. Therefore, population centers that will expand dramatically in the next 25 year, such as Atlanta, GA, Dallas, TX, Raleigh-Durham, NC, and Northern Virginia will see great increase in domestic water use, up to 200%. However, domestic use is only about 10% of the total water demand defined in Equation 1, so population growth has large impact (up to 70%) on the WSSI values in those HUCs where large cities are located but has little impact (< 5%) on the overall water supply stress at the regional scale.

## *Land Use Change Impact (Scenario 4)*

Changes in land cover and land use directly affect water availability by altering ecosystem evapotranspiration and thus water yield (precipitation - evapotranspiration). For example, reduction of forest areas or urbanization generally increases water yield. Land use changes in irrigated area also affect the amount of water demand in the irrigation sector. Consequently, areas that are subject to future urbanization such as metropolitan Atlanta (20% forest reduction) will have see reduced water stress; Areas in the Mississippi Valley with projected increases in forest lands will show slightly more water stress due to increase of forest water use.

## *Climate + Population Change Impact (Scenario 5)*

The combined changes of climate and population affect both water availability and demand, and higher water stress is expected than from changes in any individual factor. As discussed earlier, population changes will have limited effects on the overall water demand, thus the increased water stress from Scenario 5 was mostly attributed to climate change. As expected, the total impact projections depend heavily on the climate change scenarios used. An example under the CGC1 climate change scenario showed an enhanced water stress (Fig. 7).



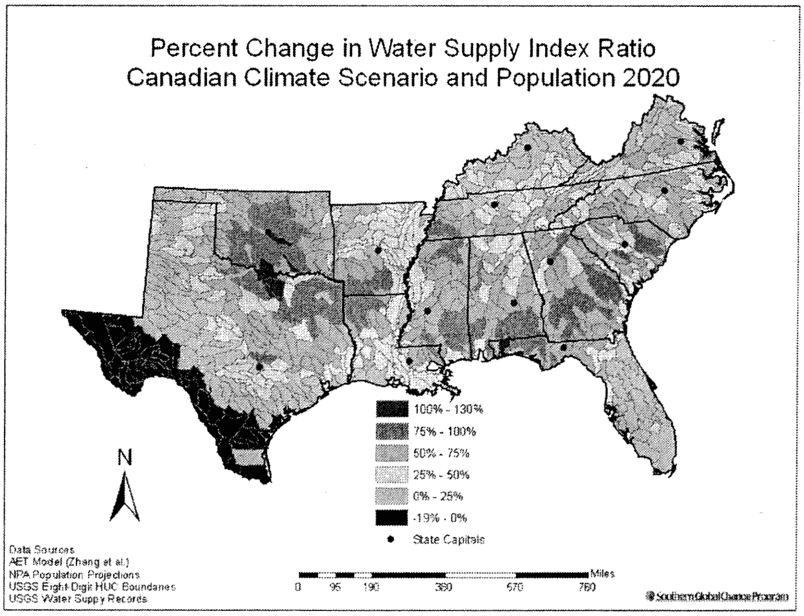




Figure 7. Combined impact of future changes in climate (Hadley and CGC1) and population (Scenario 5) on water supply stress index showing greater water stress than an individual stressor in the region east of Mississippi River.

## *Climate + Population + Land Use Change Impact (Scenario 6)*

It is interesting to examine the individual impacts of climate, population and vegetative cover change on regional water supply and demand, but in reality each of these three drivers occur simultaneously. Because urbanization and forest area decline will dominate the land use change patterns in the southern U.S., water stress is expected to be relieved somewhat from the land use change point of view. However, as discussed in Scenario 5, combined climate change (drying) and population growth will reduce water supply and increase water demand, thus generally causing increased water stress, such as in the case of the CGC1 climate scenario. The magnitude of water stress increase will exceed the limited water stress relief from land use change, and therefore, the overall WSSI is expected to increase in most of the southern U.S. However, for the Hadley scenario, due to increased precipitation east of the Mississippi River, climate change actually may reduce water stress in the southeast (Fig. 8).

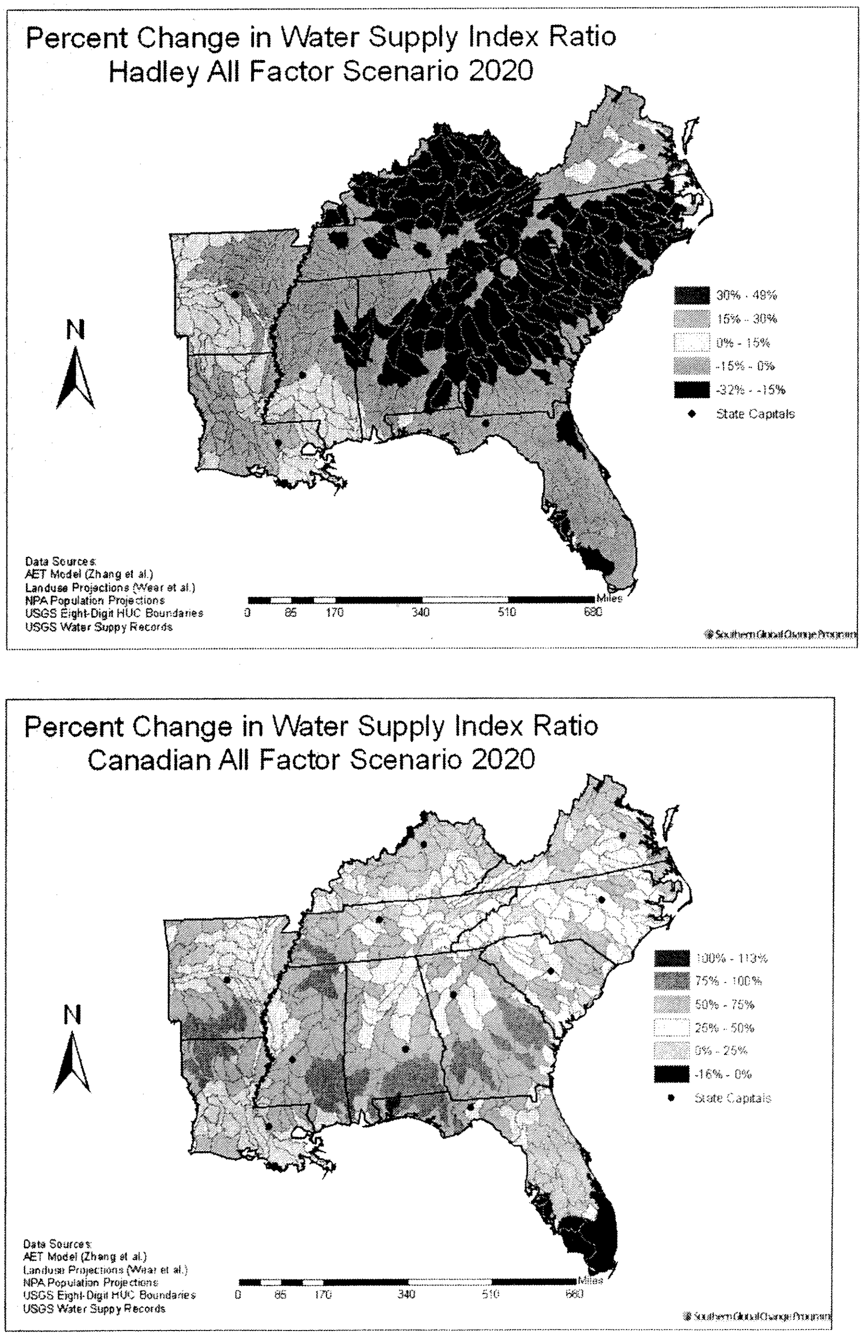



Figure 8. Combined impact of future changes in climate (Hadley and CGC1 scenarios), population, and land use (Scenario 6) on water supply stress index. Two climate change scenarios resulted in distinct water stress trend in by 2020.

## Summary

Water supply and demand issues are affected by many natural and socioeconomical factors and large uncertainties remain. This paper begins to explore the potential individual and combined impacts of climate, population, and land use change on water availability, demand, and water stress trends in the next 25 years. Across the southern US, changes in climate, population, and land use will have progressively decreasing impacts on water stress over the next 25 years. Traditionally water stressed areas with large irrigated areas or large water usage from thermoelectric facilities will expect even more stress in large population centers with increasing population and climate warming. Less populated areas that had little water shortage problems in the past may also expect to face water stress issues under changes in global and regional climate. However, future climate change induced precipitation patterns remain uncertain, especially in the eastern U.S., and thus realistically predicting future water stress remains challenging.

This work represents the first step to examine water supply and demand simultaneously at a regional scale. There are several areas that need improvement for future studies.

1). We used a rather simple definition for water supply that represents the maximum water availability (Streamflow + Returnflow + Deep groundwater withdraw) for total water withdrawal on an annual basis. In actuality, most of the streamflow will run off to major rivers and eventually to the ocean and will not be available for human use. Thus, the real water supply capacity in any basin (HUC) would be much less than the water supply term defined in the present study.

2). Our current models are using long-term average annual climate drivers. Generally, water shortages occur due to a series of unusually low precipitation years, not long-term stream flow deficits. Also, water shortages can occur within a year when water demand is highest and water yield is lowest (i.e., summer). Neither annual nor inter-annual issues are addressed in the present study.

3). The current model only compares water supply and demand within the same HUC area. In reality, large metropolitan areas seldom draw water only from local sources. In many cases (e.g., Los Angeles and New York City) water is transported from great distances, but the current model does not account for this movement. Therefore, this model may over-predict local water stress.

4). Future water use by other major water users such as thermoelectric and industry were assumed static in the present model. Empirical models are needed to project future water demands for those factors as a function of human population and economics.

Despite these shortcomings, this water accounting system can be a valuable tool for helping policy makers and public land managers to make sound decisions for the wise use of water resources.Acknowledgements

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