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IMPACTS OF MULTIPLE STRESSES ON WATER DEMAND AND SUPPLY ACROSS THE SOUTHEASTERN UNITED STATES[1]

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ABSTRACT: Assessment of long-term impacts of projected changes in climate, population, and land use and land cover on regional water resource is critical to the sustainable development of the southeastern United States. The objective of this study was to fully budget annual water availability for water supply (precipitation − evapotranspiration + groundwater supply + return flow) and demand from commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric uses. The Water Supply Stress Index and Water Supply Stress Index Ratio were developed to evaluate water stress conditions over time and across the 666 eight-digit Hydrologic Unit Code basins in the 13 southeastern states. Predictions from two Global Circulation Models (CGC1 and HadCM2Sul), one land use change model, and one human population model, were integrated to project future water supply stress in 2020. We found that population increase greatly stressed water supply in metropolitan areas located in the Piedmont region and Florida. Predicted land use and land cover changes will have little effect on water quantity and water supply-water demand relationship. In contrast, climate changes had the most pronounced effects on regional water supply and demand, especially in western Texas where water stress was historically highest in the study region. The simulation system developed by this study is useful for water resource planners to address water shortage problems such as those experienced during 2007 in the study region. Future studies should focus on refining the water supply term to include flow exchanges between watersheds and constraints of water quality and environmental flows to water availability for human use.

(KEY TERMS: climate change; land use change; regional modeling; water demand; water supply.)

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INTRODUCTION

Water resources across the United States (U.S.) have been increasingly stressed over the past two decades, mainly due to population growth and climate change and variability (Gleick, 2003). A partial survey by the U.S. General Accounting Office (GAO) revealed that many western (e.g., Colorado) and eastern (e.g., South Carolina) states were expecting significant local or regional water shortages. A full picture of water availability and use at the national or local levels is not available: a comprehensive water assessment has not been done for 25 years

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(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) also expressed an urgent need for developing the science and tools needed to precisely quantify current and future human water demands (WD) and water supply at multiple scales. National-scale dialogs organized by the American Water Resource Association (AWRA, 2005) on water resource policy concluded that an integrated assessment of water resources and information sharing was an important step toward preventing future water crises.

The southeast has the fastest population growth rate in the U.S. Population increased 14% between 1990 and 2000, and is expected to increase another 24% in the next 20 years. 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; USGCP, 2000). Climate change may affect many aspects of natural ecosystems, as well as the regional economy. For example, the amount of water withdrawal for crop irrigation is expected to increase as precipitation decreases and evapotranspiration increases with higher air temperature (Peterson and Keller, 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 20-40 years (Wear, 2002). For example, the total urban area has increased more than 200% from 1945 to 1992. Although total forest area did not change greatly in the past decade, large areas of land in the same parts of the region (e.g., Florida, Piedmont region of North Carolina) have been lost to urban uses, while agricultural areas in the lower Gulf coastal plains have been reforested (Wear, 2002). The combination of these factors may predispose the southern U.S. to water resource changes in the coming decades.

Unfortunately, modeling tools needed to assess and project regional water availability and use are lacking. Individually, hydrological models have been coupled with GCM predictions of climate change (McNulty *et al.*, 1997; Arnold *et al.*, 1999; Sun *et al.*, 2005; Jha *et al.*, 2006), demographic models of population change (NPA Data Services Inc., 1999), and land use change models (Hardie *et al.*, 2000; Wear, 2002). However, these individual models are designed to work at different spatial and temporal scales and are not meant to interact for assessing potential water resource stress at a regional scale. Additionally, these models were not developed for evaluating both natural and human impacts on water resources. As illustrated in Figure 1, factors influencing both water availability and use are closely linked, and their interactions are more complex than their individual processes. Most of the existing regional scale water resource assessments treated water supply and water withdrawals separately. Few studies have addressed the combined interactions of water supply and demand. For example, Arnold *et al.* (1999) mapped the water balances for the continental U.S. using the HUMUS hydrologic model, and later the model was applied (Brown *et al.*, 1999; Thomson *et al.*, 2003) to examine how global climate, including atmospheric CO_2 and El Nino/Southern Oscillation, impact water yield. Similarly, Wolock and McCabe (1999) evaluated the impacts of climate change on the water balances of the conterminous U.S. with a monthly time step hydrologic model. However, few studies are available to examine the impacts of multiple stresses on water resources at the regional or the continental U.S. scale. Using historic U.S. Geological Survey (USGS) water use (WU) data, Brown (2000) projected freshwater withdrawals for the next 40 years for seven economic sectors including livestock, domestic and public, industrial and commercial, thermoelectric, and irrigation. This work suggests that water withdrawals in the U.S. will stay within 10% of the 1995 level. This study did not consider effects of future climate and land use changes and assumed static water availability (Brown, 2000). Also, the spatial scale was large water resources regions, which were considered rather coarse for use by local water managers. Roy *et al.* (2005) projected water withdrawals at a much finer scale (county level) across the U.S. from 2000 to 2025 by combining an extrapolation of historic WU trends (Solley *et al.*, 1998; Hutson *et al.*, 2004) with two projections of

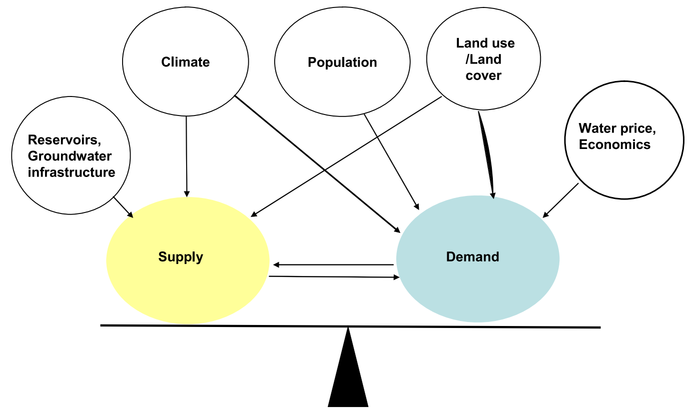

FIGURE 1. Factors Affecting Water Supply and Demand and Their Relations.

energy use, population growth, and WU efficiency. This study did not compute the full water budget (e.g., actual evapotranspiration losses) and thus was limited in projecting water supply and demand relationships. Roy *et al.* (2005) recommend an improved national comprehensive water sustainability assessment with finer spatial resolution and the effects of instream ecosystem WU and climate change on water availability.

This study attempts to address some of the research gaps in previous regional scale water resource studies by: (1) developing an integrated modeling approach that combines an annual water yield model with climate, land use/land cover, and population change projections to assess water supply stress that reflects water supply, and WU by multiple users; and (2) applying the modeling system to project water stress over the next 20 years under different scenarios of climate, land management, and population growth across the 13 southern states.

METHODS

The guideline for a full accounting of both water supply and water use components was the watershed budget of a basin, as shown in Figure 2. In this study, we used the USGS Hydrologic Unit Code (HUC) watershed as the working scale. There are 666 eight-digit HUC (994) watersheds in the southern U.S. (U.S. Geological Survey, Water Resources Division, 1994), as defined by the 13 states from Virginia to Texas. The databases described below include historic WU and return flow rates (RFR) by WU sectors, groundwater withdrawal, historic and projected climate, population, and land use. These databases came in different temporal and spatial scales. All databases were scaled to the eight-digit HUC watershed level for hydrologic simulation and water stress computation. Once databases were assembled, alternative scenarios were developed to individually and collectively quantify the impacts of climate, land use, and population changes on water supply and demand.

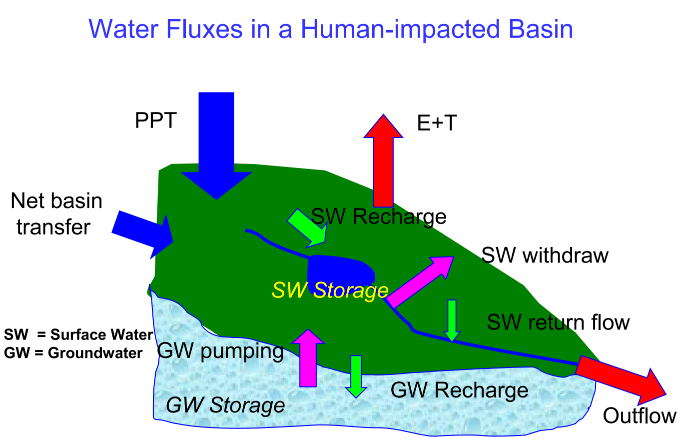

FIGURE 2. Schematic Sketch of Water Flows and Storage in a Human-Impacted Basin.

Historical Water Withdrawals and Use

The 1995 and 2000 national anthropogenic WU survey datasets published by the USGS were initially evaluated for determining historic WD. Overall, the two survey periods recorded similar WU (Solley *et al.*, 1998; Hutson *et al.*, 2004; Roy *et al.*, 2005). Therefore, we used 1995 datasets as our baseline for comparison purposes. USGS water survey grouped water users into seven categories: commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric. At the national scale, these sectors represent 3, 7, 8, 41, 1, 1, and 39% of the total use, respectively. In the southeastern U.S., thermoelectric water withdrawal dominates, followed by irrigation centered in the Mississippi valley and western Texas regions. However, because the RFR from power plants are high (>90%), irrigation is the largest sector in terms of consumptive WU (74% of total) followed by thermoelectric use (17%). Over half of the water withdrawal is derived from groundwater in the Mississippi valley, western Texas, and coastal regions.

Historic and Projected Climate Data

Historic monthly climate data (i.e., precipitation and air temperature) compiled by the VEMAP group (Kittel *et al.*, 1997) were used as the baseline to which the climate change scenarios were compared. The climate data were in a gridded 0.5° by 0.5° (about 50 km by 75 km) format for the continental U.S. From this national database, we derived historic data from 1985 to 1993 as the climate baseline across the 13 southern states. Then, the gridded climate datasets were overlaid to the eight-digit HUC watersheds. Air temperature and precipitation data that drive the evapotranspiration and water balance models are described later.

Two future climate change scenarios (Kittel *et al.*, 1997) were acquired from predictions by the HadCM2Sul model, developed by the United Kingdom Hadley Climate Research Center, and the CGC1 model, developed by the Canadian Climate Centre, representing warm and wet and hot and dry scenarios, respectively. Both climate projections were derived from transient global climate models and are widely used by the climate change research community

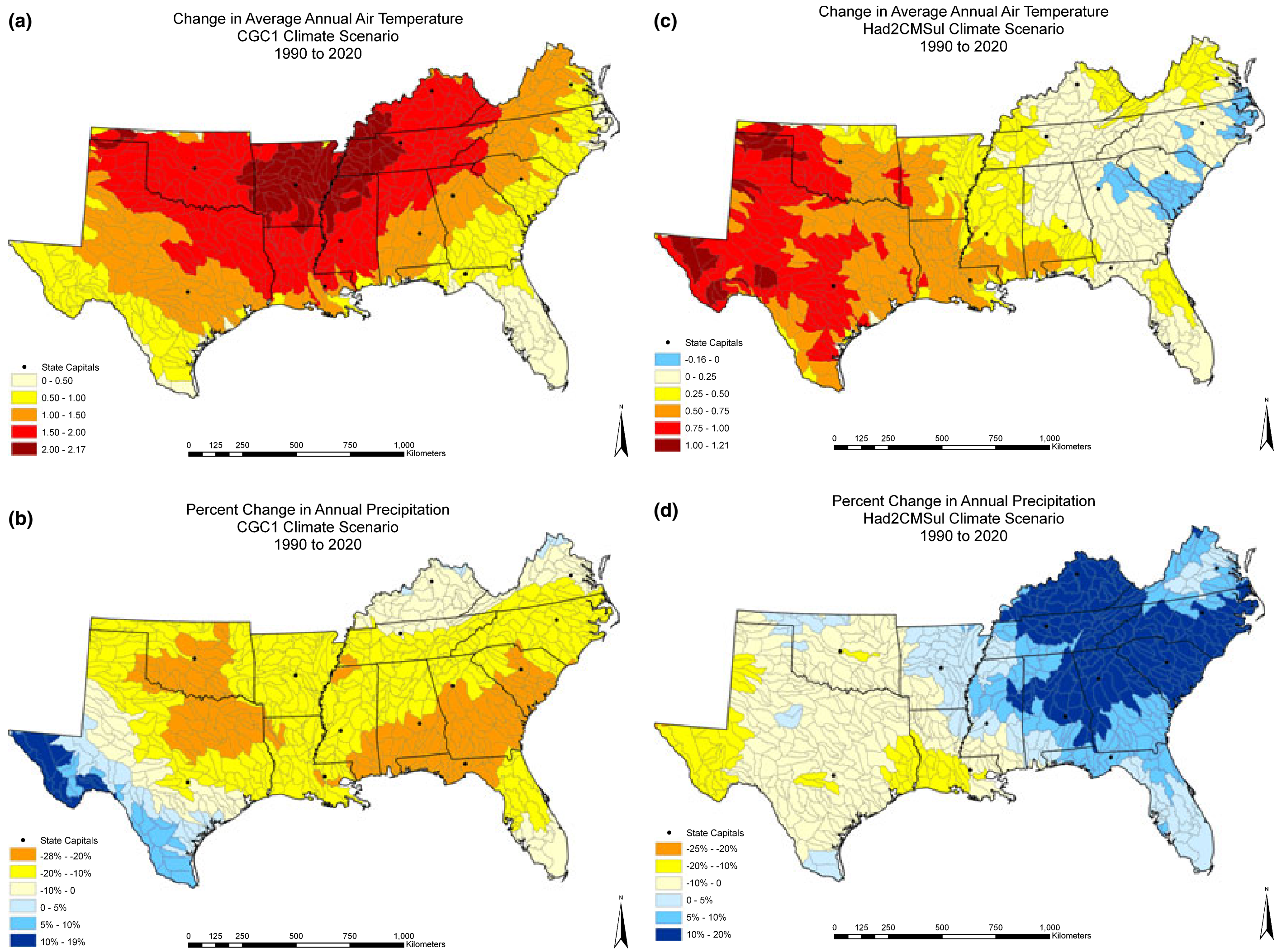

FIGURE 3. Predicted Changes in Air Temperature and Precipitation Across the Southern U.S. by the CGC1 Model (a and b) and the HadCM2Sul (c and d) Model in 2020.

(McNulty *et al.*, 1997; Wolock and McCabe, 1999; National Assessment Synthesis Team, 2000; Jha *et al.*, 2006). When compared to the average historic climate (1985-1993), HadCM2Sul projects that, by 2020, the region east of the Mississippi River will experience up to 20% increase in annual precipitation and a moderate increase in air temperature, and west of the Mississippi River a decrease in precipitation of up to 10% and an increase in air temperature (>0.5°C). In contrast, the CGC1 model predicts that most of the southern U.S. will have a 10% decrease in precipitation and a large increase in air temperature (1-2°C) by 2020 (Figure 3).

Historic and Projected Population Data

The 1990 U.S. Census Bureau records showed that approximately 100 million people lived in the 13 southern states at that time (U.S. Census, 2002). Population projections at the census block level were available out to the year 2050 (NPA Data Services Inc., 1999). We aggregated the projected data to the eight-digit HUC watershed for each year between 2000 and 2020. We used 1995 as our population baseline and 2020 as the population change scenario endpoint. Between 1995 and 2020, the southern U.S. population was predicted to increase by more than 50% (NPA Data Services Inc., 1999). Population growth by 2020 will not be uniform, varying from −13 to +135% across the region when compared to 1995 levels (Figure 4). No new areas of growth were forecasted, but current urban centers are expected to expand, and rural areas are generally expected to become more densely populated. Many metropolitan areas and Capital cities will double their population by 2020 (Figure 4).

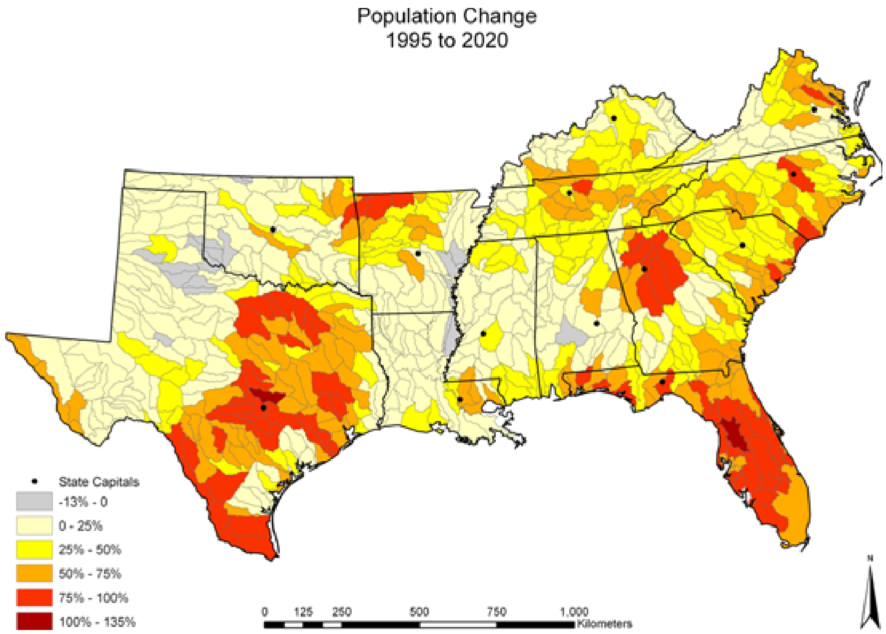

FIGURE 4. Projected Population Changes in the Southern U.S. by 2020 (NPA Data Services Inc., 1999). Data are aggregated from census block to the HUC level.

Historic and Projected Land Use Change

The 1992 National Land Cover Data (NLCD) (http://edc.usgs.gov/glis/hyper/guide/mrlc) with a 30-m spatial resolution was used as the land use/land cover baseline. All land use/land cover classes were aggregated into five major categories according to their hydrologic properties. These include forests (conifers or hardwoods), croplands, urban/residential, and water bodies. Land use is a major driver for the annual hydrologic model for estimating evapotranspiration by watershed as described in the next section. Land use changes from the 1992 baseline to 2020 were projected using a county-level economic model (Hardie *et al.*, 2000). Changes in land area allocation among urban/residential, croplands, and forest use areas are driven by population density, personal income, housing values, and timber prices. The projection used for this study suggests that urbanization dominates land use change patterns: urban areas will increase from 8 million to 22 millions hectares by 2020. Urban areas are expecting to increase by 17% (0-85%) (Figure 5), while forest lands will decrease by 2% (–21 to 10%) and croplands decrease by 2% (13-36%) at the eight-digit HUC watershed scale (Wear, 2002). Because the land use model did not predict changes in irrigated lands, this study assumed that the proportion of irrigated lands would not change over time, although the total area would change as a result of urbanization. Land use change data were not available for Texas or Oklahoma; therefore, these states were excluded from some scenario analyses.

Definitions of Water Supply, Demand, and Stress Index

Water supply was defined as the total potential water available for withdraw from a basin, expressed by the following formula:

$$\mathrm{WS} = \mathrm{SS} + \mathrm{GS} + \sum \mathrm{RF}_i,$$

where WS is total water supply volume (m^3) for each HUC; SS is total surface water supply for each HUC. SS is $P - \mathrm{ET}$, assuming no change in watershed water storage at the annual time scale; P is precipitation; ET is watershed evapotranspiration calculated by an empirical formula as a function of potential evapotranspiration, precipitation, and land cover type (Sun *et al.*, 2005). The ET term was estimated by the following formula:

$$\frac{\mathrm{ET}}{P} = \frac{1 + w\frac{\mathrm{PET}}{P}}{1 + w\frac{\mathrm{PET}}{P} + \frac{P}{\mathrm{PET}}},$$

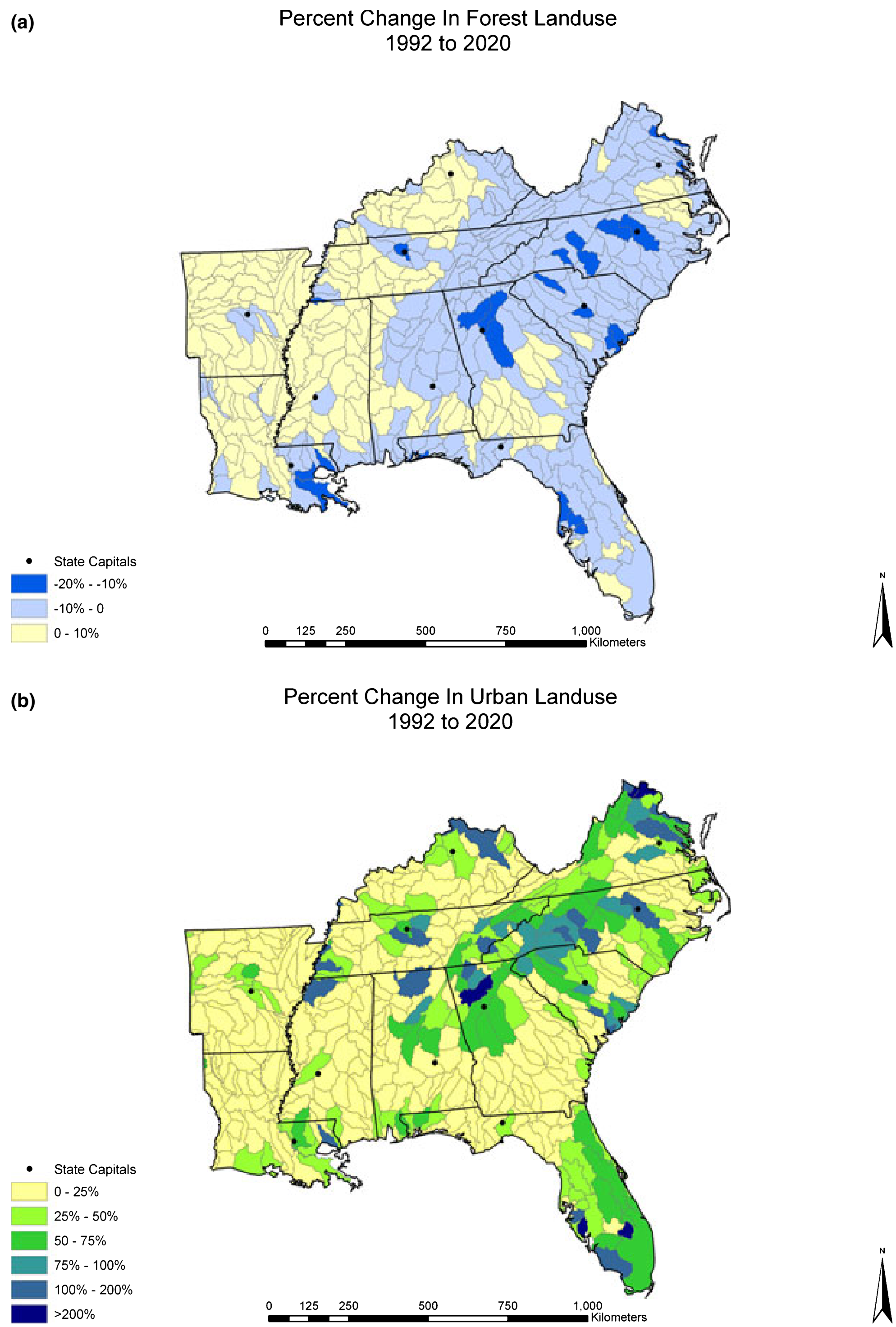

FIGURE 5. Projected Land Use Changes in Forest (a) and Urban (b) Lands in the Southern U.S. by 2020 Showing a Large Increase in Urban Lands in the Piedmont Physiographic Region and Florida.

where w is the plant-available water coefficient and represented the relative difference of WU for transpiration. The value of w varies from 2.0 to 2.8 for non-urban land uses as reported in Sun *et al.* (2005). PET was calculated on a monthly basis and summed as annual total for use in annual ET estimation.

For a watershed with mixed land uses

$$\mathrm{ET} = \sum (\mathrm{ET}_k \times f_k),$$

where f_k is the percentage of land use k including conifers, deciduous, mixed forest, grasslands/crops, residential, and water bodies.

ET was calculated at an annual time step and a special scale of half a degree of latitude and longitude. Then, SS was scaled up to the eight-digit HUC level. Satisfactory model validations against ET at the watershed scale and water yield at the regional scale were conducted. Details about ET model performance can be found in Sun *et al.* (2005).

GS is total ground-water supply as represented by USGS annual historical (1995) ground water withdrawal records (Solley *et al.*, 1998). RF is return flow from each of seven water users *i* including commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric sectors. RF is calculated as the USGS historical (1995) (Solley *et al.*, 1998) RFR multiplied by the WU; RFRs vary among watersheds and WU sectors. For example, RFRs for the domestic use sector have an average of about 67%, and the thermoelectric sector has a higher rate (>70%) with most of the watersheds having a rate greater than 90%.

WD represents the sum of all WU by each of the seven sectors plus public (PB) use and losses which represent water transfer between basins and the difference between water withdrawn by public suppliers and the water delivered by public suppliers (Solley *et al.*, 1998)

$$\mathrm{WD} = \sum \mathrm{WU}_i + \sum \mathrm{PB}_i \quad i = 1-7$$

We proposed two terms, Water Supply Stress Index (WaSSI) (Equation 1) and Water Supply Stress Index Ratio (WaSSIR) (Equation 2). The term WaSSI was used to quantitatively assess relative magnitude in water supply and demand at the eight-digit HUC watershed level. The term WaSSIR was used to assess the relative change in WaSSI between the baseline scenario (x = 1) and one of the future scenarios (x = 2-6) as described in next section. Positive WaSSIR values indicate increased water stress and negatives indicate reduced water stress when compared to historical water stress conditions (Scenario 1)

$$\mathrm{WaSSI}_x = \frac{\mathrm{WD}_x}{\mathrm{WS}_x} \tag{1}$$

and

$$\mathrm{WaSSIR}_x = \frac{\mathrm{WaSSI}_x - \mathrm{WaSSI}_1}{\mathrm{WaSSI}_1}, \tag{2}$$

where x represents simulation scenarios described in the next section of this paper.

For future WD estimation, we focused on three major WU sectors, domestic, irrigation, and thermoelectric plants. Changes in water uses affect the amount of total water supply due to the return flow component of WS. WD for domestic WU was predicted by correlating USGS historical WU (million gallons per day) in the domestic sector and the population (in thousand persons) for 1995 at the eight-digit HUC watershed level.

$$\text{Water use in the domestic sector} = 0.114 \times \text{population}, \quad R^2 = 0.95, n = 666 \tag{3}$$

Similarly, WD for irrigation WU was predicted by correlating USGS historical WU (million gallons per day) in the irrigation sector and the irrigation area (in thousand acres) for 1995 at the eight-digit HUC level.

$$\text{Water use by irrigation} = 1.3714 \times \text{irrigation area} + 2.07, \quad R^2 = 0.67, n = 666 \tag{4}$$

Future water withdrawal by thermoelectric power plants (mainly fossil fuel and nuclear plants) is

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

Scenario and Land Cover	Land Use/Land Cover	Climate	Population
1: Baseline	1992 MRLC	Historic data (1985-1993)	1990 census
2: Climate change	1992 MRLC	GCM projections (HadCM2Sul and CGC1)	1990 census
3: Population change	1992 MRLC	Historic data	Projected to 2020 (NPA)
4: Land use change	Projected to 2020	Historic data	1990 census
5: Climate + population change	1992 MRLC	GCM projections	NPA
6: Climate + population + land use change	Projected to 2020	GCM projections	NPA

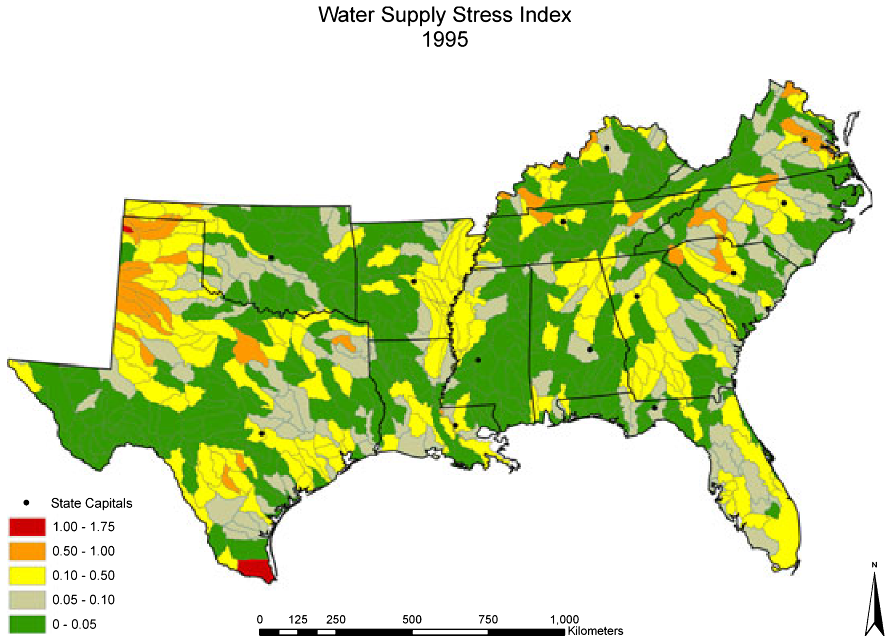

FIGURE 6. Modeled Historical (1985-1993) Water Supply Stress Index (WaSSI) Showing Overall Higher Stress in Western Texas and the Mississippi Valley and Stress in Local Areas With Water Use by Power Plants.

predicted as a function of population growth and rate of WU per electric power unit (kilowatt-hours) generated by thermoelectric plants. Thus, we used the following formula to calculate WU by the thermoelectric sector in 2020 with 1995 as our baseline (Brown, 2000).

$$\text{Water use by the thermoelectric sector} = \text{population} \times (\text{total electricity in kilowatt-hours use per person}) \times \text{percentage of electricity generated by thermoelectric plants over total electricity} \times \text{water withdrawal per kilowatt-hours of electricity generated by thermoelectric plants} \quad (5)$$

Total electricity is thermoelectric plus hydroelectric power. WU efficiency by power plants has been increasing since the 1960s, so we assumed future WU per kilowatt-hour to decrease by 0.6% annually as a conservative estimate (Brown, 2000). Therefore, water withdrawal per kilowatt in 2020 = water withdrawal per kilowatt in 1995 × $(1 - 0.006)^{15}$.

Historic data in 1995 and 2000 suggested little change in WU for the smaller sectors. So, future WU by the other four sectors (livestock, commercial, mining, and industry) were assumed to remain equal to the 1995 level. Similar assumptions were made by Brown (2000) and Roy *et al.* (2005) for projecting future WD.

Simulation Scenarios

Six scenarios were developed to examine historic and future water stress under historic or projected changes in climate, population, and land use by one factor or a combination of the three factors (Table 1). Scenario 1 represented the average historic (i.e., 1985-1993) climate, population distribution (1995), and land cover conditions (1992) across the 13 southern states. Calculations of water supply and WD for Scenario 1 served as the baseline for comparisons among water stress conditions under alternative climate, population, and land cover conditions. Scenario 2 represented predicted climatic changes according to two GCMs (HadCM2Sul and CGC1) on water supply, WD, and stress indices (WaSSI and WaSSIR) by 2020 without population or land use changes. Similarly, Scenario 3 examines the impacts of predicted changes in human population by 2020 and assumes no climate or land use changes. Population change will mainly affect total WD, both the domestic WU and thermoelectric WU sectors. Scenario 4 was designed to examine impacts of land use change. As illustrated in Figure 1, land use change affects the water availability (water yield and evapotranspiration loss) and WD (WU by irrigated crops). So land use change affects both the water supply and demand terms. A high degree of certainty exists for dramatic change of both population growth and urbanization in the study region (Wear, 2002).

TABLE 2. Historic Water Supply Stress Index and Change Under Multiple Stresses for Selected Watersheds and the Southeastern U.S.

	Baseline Water Supply Stress Index (WaSSI) and Impacts on WaSSI From Scenarios 2-5								
		Scenario 2: Climate Change				Scenario 5: Climate + Population		Scenario 6: Climate + Population + Land Use	
Capital City, State, and Watershed Number (HUC)	**Scenario 1: Baseline WaSSI**	**Had2CMSul**	**CGC1**	**Scenario 3: Population Change**	**Scenario 4: Land Use Change**	**Had2CMSul + Population**	**CGC1 + Population**	**Had2CMSul + Population + Land Use**	**CGC1 + Population + Land Use**
Montgomery, Alaska 3150201	0.072	−16.34%	54.9%	3.6%	−1.2%	−13.3%	60.2%	−14.2%	57.5%
Little Rock, Arkansas 11110207	0.149	−1.7%	37.0%	3.7%	−5.2%	2.0%	41.9%	−3.2%	32.4%
Tallahassee, Florida 3120001	0.088	−10.7%	44.8%	31.0%	−5.4%	17.3%	87.3%	11.6%	74.9%
Atlanta, Georgia 3130002	0.248	−15.9%	38.6%	24.1%	−4.4%	5.7%	67.1%	1.8%	58.4%
Frankfort, Kentucky 5100205	0.098	−20.9%	14.7%	16.6%	−1.6%	−7.5%	33.5%	−8.7%	30.9%
Baton Rouge, Louisiana 8070202	0.250	14.0%	38.8%	16.9%	−2.9%	32.4%	59.2%	28.2%	53.1%
Jackson, Massachusetts 3180002	0.035	−3.0%	58.3%	11.7%	−0.9%	8.4%	76.4%	7.5%	74.0%
Raleigh, North Carolina 3020201	0.103	−19.4%	41.0%	32.5%	−13.0%	7.3%	85.0%	−4.5%	54.8%
Oklahoma City, Oklahoma 11100302	0.040	24.0%	73.9%	14.4%	n/a	41.7%	98.4%	n/a	n/a
Columbia, South Carolina 3050110	0.231	−14.9%	41.1%	4.6%	−9.8%	−10.9%	46.9%	−18.7%	29.4%
Nashville, Tennessee 5130202	0.189	−16.9%	19.9%	8.2%	−8.6%	−9.9%	29.3%	−16.5%	15.5%
Austin, Texas 12090205	0.420	12.2%	15.5%	24.6%	n/a	37.3%	40.7%	n/a	n/a
Richmond, Virginia 2080205	0.119	−7.0%	24.6%	6.6%	−2.5%	−0.9%	32.6%	−3.2%	28.5%
Southeastern U.S.	0.146	−5.0%	33.8%	11.5%	−7.9%	6.0%	48.3%	−6.2%	37.0%

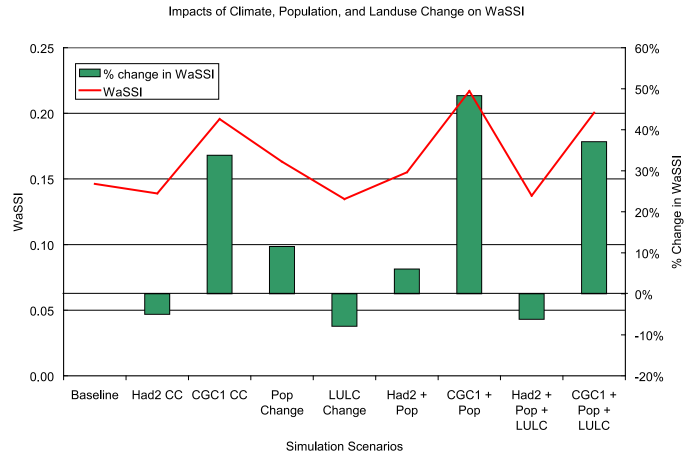

FIGURE 7. Overall Impacts of Climate Change, Land Use Change, Population Change on Water Supply Stress Index (WaSSI = Water Demand/Water Supply) in 2020. Changes in WaSSI are determined by comparing WaSSI in 2020 for each scenario and the baseline WaSSI in 1995.

Scenario 5 examined the combined effects of future climate and population changes to identify areas that would likely experience the worst water stress (Table 1). Scenario 6 combined all three stressors to study the overall consequences of changes in climate, population, and land use in 2020.

RESULTS

Scenario 1: Baseline

Precipitation and air temperature are the most important determinants of water loss by evapotranspiration and thus water availability across the southern U.S. (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 annually receive almost 200 cm of precipitation. Average annual air temperature is roughly inversely proportional to latitude within the region. Therefore, the Appalachians and the Gulf coast had the highest water supply, 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 WaSSI (Figure 6). Identified stressed areas also included southern Florida, southern Georgia, and the Mississippi valley areas that depend on irrigated agriculture and had high

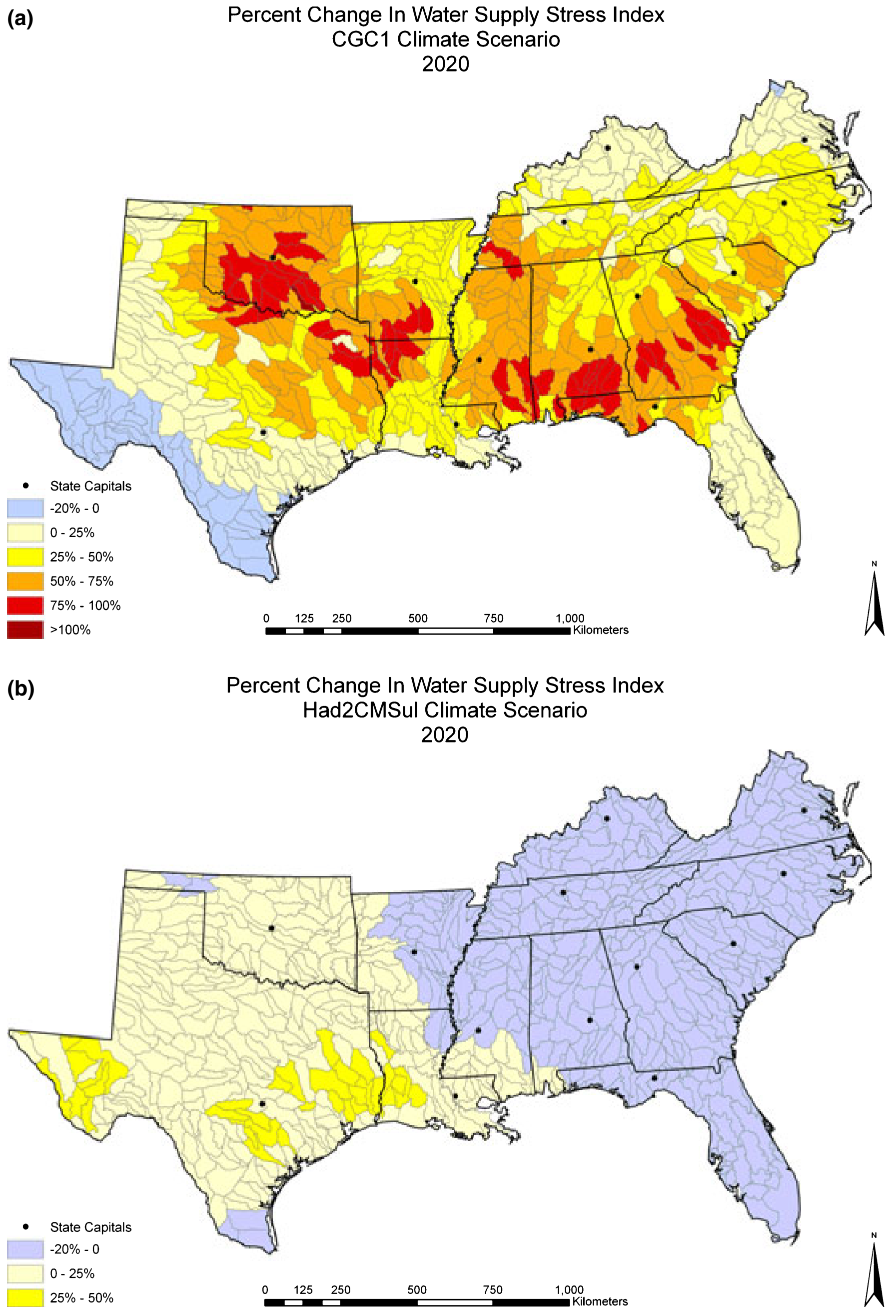

FIGURE 8. Modeled Impact of Climate Change (CGC1) (a) and HadCM2Sul (b) Projections on Water Supply Stress Index (WSSI) Showing Distinct Trends in Water Stress Across the Southern U.S. in 2020.

evapotranspiration loss. Several isolated eight-digit HUC watersheds in high precipitation regions east of the Mississippi River (e.g., North Carolina) also showed high water stress, primarily due to high thermoelectric WD.

Among the 13 southern capital cities, Austin, Texas, and Baton Rouge, Louisiana, had the highest and second highest WaSSI values of 0.42 and 0.249, respectively (Table 2). Atlanta, Georgia, had a similar WaSSI as Baton Rouge. Those three cities experienced high water supply stress for different reasons. Austin had a high WaSSI mainly due to low water availability (supply) while Baton Rouge and Atlanta had high WD due to population pressure. The weighted average WaSSI value for the study region (i.e., 0.146) (Figure 7) was much lower than the selected large cities, suggesting a more complex water stress pattern at the regional scale. Human population was only one of the driving factors that caused water stress. In fact, in many cases, population played a minor role in the overall water stress as domestic WU was only a small portion of total WU

(<15%) in many watersheds (Solley *et al.*, 1998). To have a comprehensive balanced water stress assessment, other factors affecting both water supply and demand should be included.

Scenario 2: Climate Change Impacts

Compared to historic (1985-1993) hydrologic conditions, annual precipitation and evapotranspiration in 2020 were projected to either slightly increase, or decrease dramatically depending on the GCM used. Simulations suggested a large regional decrease in water yield using the CGC1 scenario due to a large increase in air temperature and moderate decrease in precipitation, but a large increase in water yield using the HadCM2Sul over the eastern part of the region due to a large increase in precipitation and a moderate increase in air temperature. This contrast between the two scenarios was most pronounced in the Piedmont and mountain regions that generally had higher runoff than the coastal zones. As a result, WaSSI values increased up to 106% (i.e., WaSSIR = 106%) for individual eight-digit HUC watershed under the CGC1 scenario (Figure 8). In contrast, WaSSI values were projected to decrease as much as 20% (i.e., WaSSR = −20%) east of the Mississippi Valley under the HadCM2Sul scenario. West of the Mississippi valley also showed an increased water stress pattern of lesser magnitude when compared to the CGC1 scenario. It appeared that precipitation patterns dominated water stress impacts from climate change for the southern region. Similar findings are reported in Jha *et al.* (2006) on the hydrologic sensitivity to climate change.

Among the 13 southern U.S. capital cities, under the HadCM2Sul "wet" climate change scenario, most of the cities showed reduced water stress. Some historically high water stress cities such as Raleigh, North Carolina, and Atlanta may benefit from climate change in terms of water stress decrease, where the WaSSI decreased by 16-19%. However, some cities such as Austin increased water stress up to 12%. Under the CGC1 "dry" scenario, all of the selected cities had large increases in water stress. Traditionally low water stress cities such as Oklahoma City, Oklahoma; Montgomery, Alaska; and Jackson, Massachusetts had proportionally higher water stress impacts as measured by WaSSIR. Austin had a relatively low change (16%) in WaSSI, but because the water stress has been high (0.42), future increase in water stress from 0.420 to 0.486 will aggravate the water stress.

Across the study region, average water stress was predicted to decrease slightly by 5% under the HadCM2Sul climate scenario, but increase greatly (34%) under the CGC1 climate change scenario (Table 2) (Figure 7). As in other impact studies (Jha *et al.*, 2006), the two GCMs predicted different future precipitation patterns for the study region, resulting

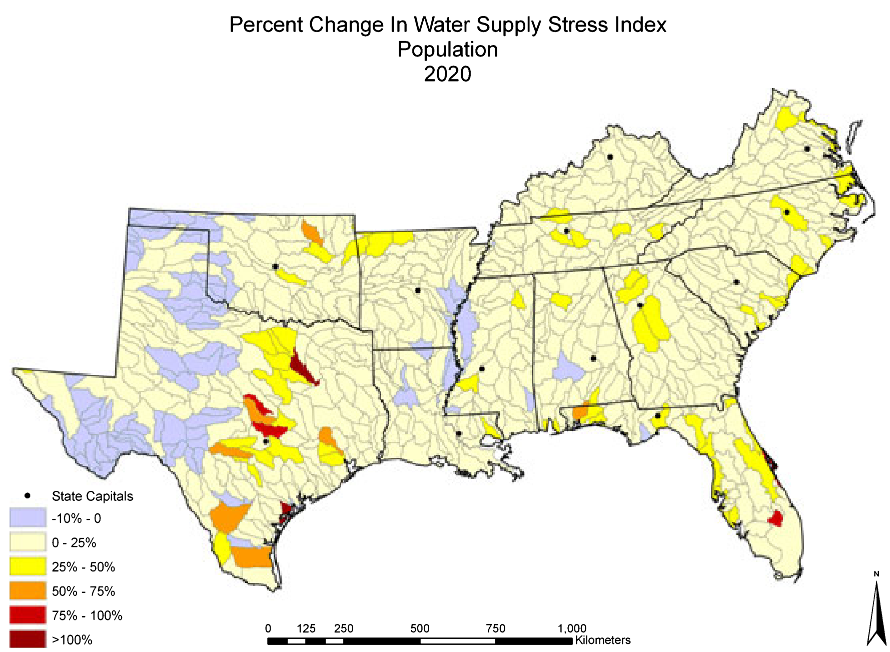

FIGURE 9. Modeled Impact of Population Growth on Water Supply Stress Index (WSSI) Showing Minor Changes in Water Stress Across the Southern U.S. in 2020.

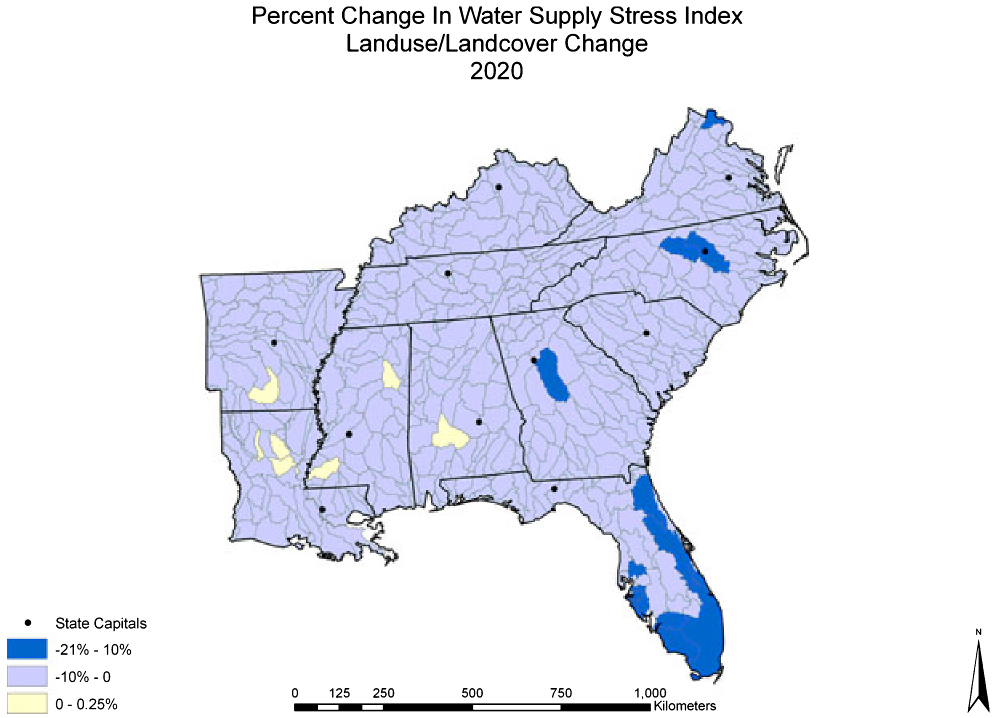

FIGURE 10. Modeled Impact of Land Use Change on Water Supply Stress Index (WSSI) Showing Minor Changes in Water Stress Across the Southern U.S. in 2020.

in different hydrologic conditions and distinctly different water stress patterns. Reducing the uncertainty in climate predictions at the watershed to regional scale was urgently needed for future impact assessment studies to provide a realistic forecast of water stress to resource managers.

Scenario 3: Population Change Impacts

The amount of water demanded by the domestic and thermoelectric WU sectors was directly related to population growth (see Equations 3 and 5). As expected, a large increase in WD and a little increase in water supply due to increase in return flow will result in an increase in WaSSI overall. Therefore, population centers that were traditionally under high water stress due to large domestic WU would see even more water stress with further population growth by 2020. This is most evident in Texas where water supply is low due to low precipitation (Figure 9). Several cities in Texas were projected to increase their WaSSI by more than 50%. Other cities such as Raleigh; Tallahassee, Florida; and Atlanta also showed large increase in WaSSI (Figure 9) (Table 2). Overall, across the region, the increase in population resulted in a 12% increase in WaSSI (Table 2) (Figure 7).

Scenario 4: Land Use Change Impacts

Changes in land cover and land use directly affected water yield (i.e., precipitation, evapotranspiration) by altering the ecosystem evapotranspiration loss, and thus water supply. For example, the reduction in forest area or urbanization generally increases total water yield (Sun *et al.*, 2005) and thus available for withdrawal. Land use changes in agriculture (i.e., irrigated area) also affected the amount of WD in the irrigation sector (see Equation 4). Consequently, watersheds that were subject to future urbanization (e.g., metropolitan Atlanta) or significant forest loss (e.g., several basins in North Carolina predicted to have a >20% forest reduction) would see reduced water stress due to land use change alone. Several watersheds showed slightly increased water stress because of increased WU from reforestation (Figure 10). Overall, across the region, water stress was projected to decrease by 8% (0-21%) with most reductions occurring in Florida and the Piedmont regions (Figures 7 and 10). Those watersheds had the highest urban land expansion (100-200%) and forest land reduction (10-20%) (Figure 5). Regions that had natural low runoff production would see the highest water stress reduction. For example, the Raleigh area in North Carolina is projected to decrease water stress by as high as 16% due to increase in water availabil-

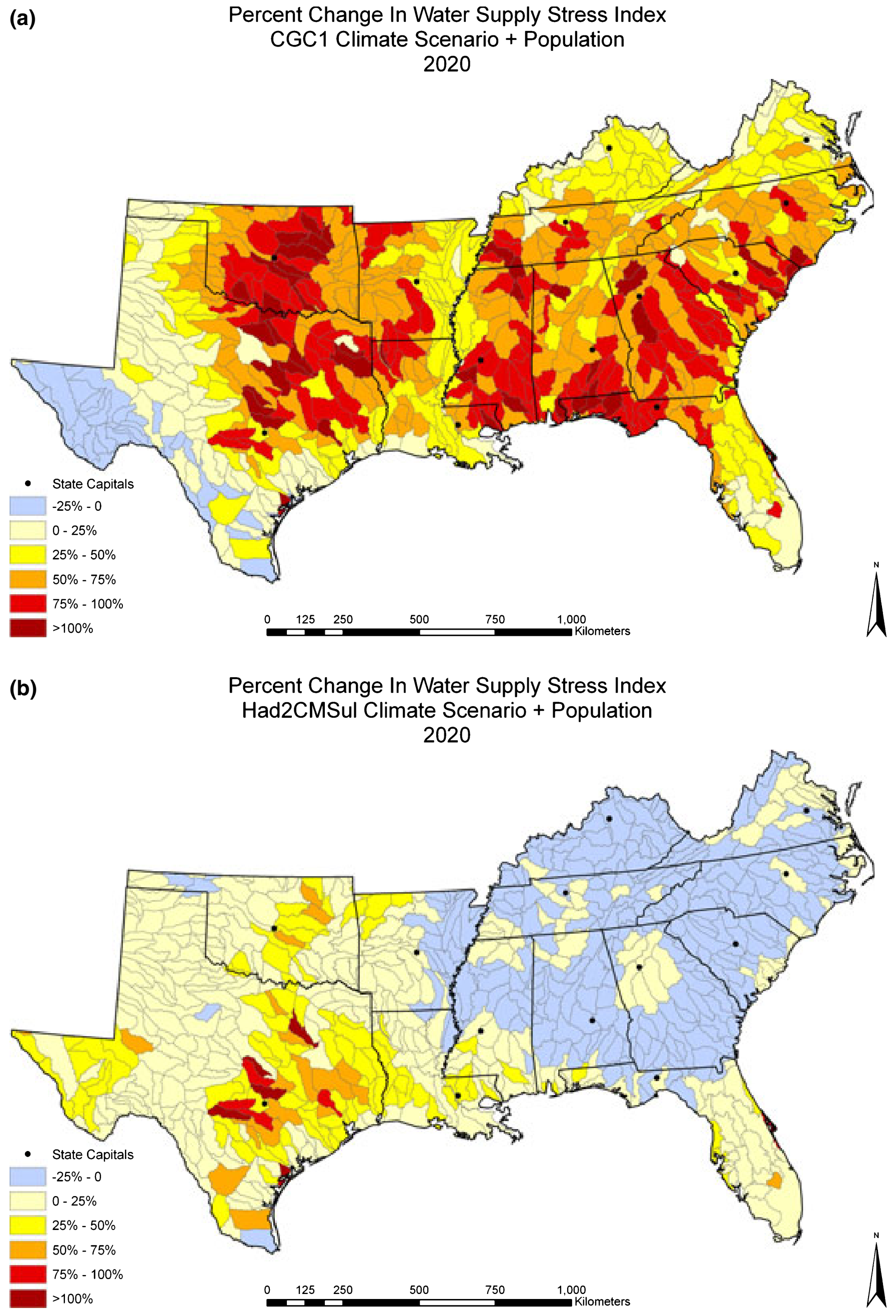

FIGURE 11. Combined Impact of Future Changes in Climate (CGC1) (a) and HadCM2Sul (b) and Population Growth (Scenario 5) on Water Supply Stress Index Showing Increased Water Stress Dominated by Climate Change in 2020.

ity as a result of forest removal (i.e., decreased forest WU) (Table 2).

Scenario 5: Climate and Population Change Impacts

The combined changes in climate and population affect both water supply and demand. The combined impacts are the result of additive effects of the two individual factors. As discussed earlier, population changes had limited effects on the overall WD at the regional scale, thus the increased water stress from Scenario 5 was mostly attributed to climate change and depended heavily on the climate change scenarios applied. Basins with large population saw a dramatic increase in water stress under the CGC1 scenario, but most of the watersheds east of the Mississippi Valley saw decreased water stress under the HadCM2Sul (Figure 11). However, large cities such as Raleigh, Atlanta, and northern Virginia

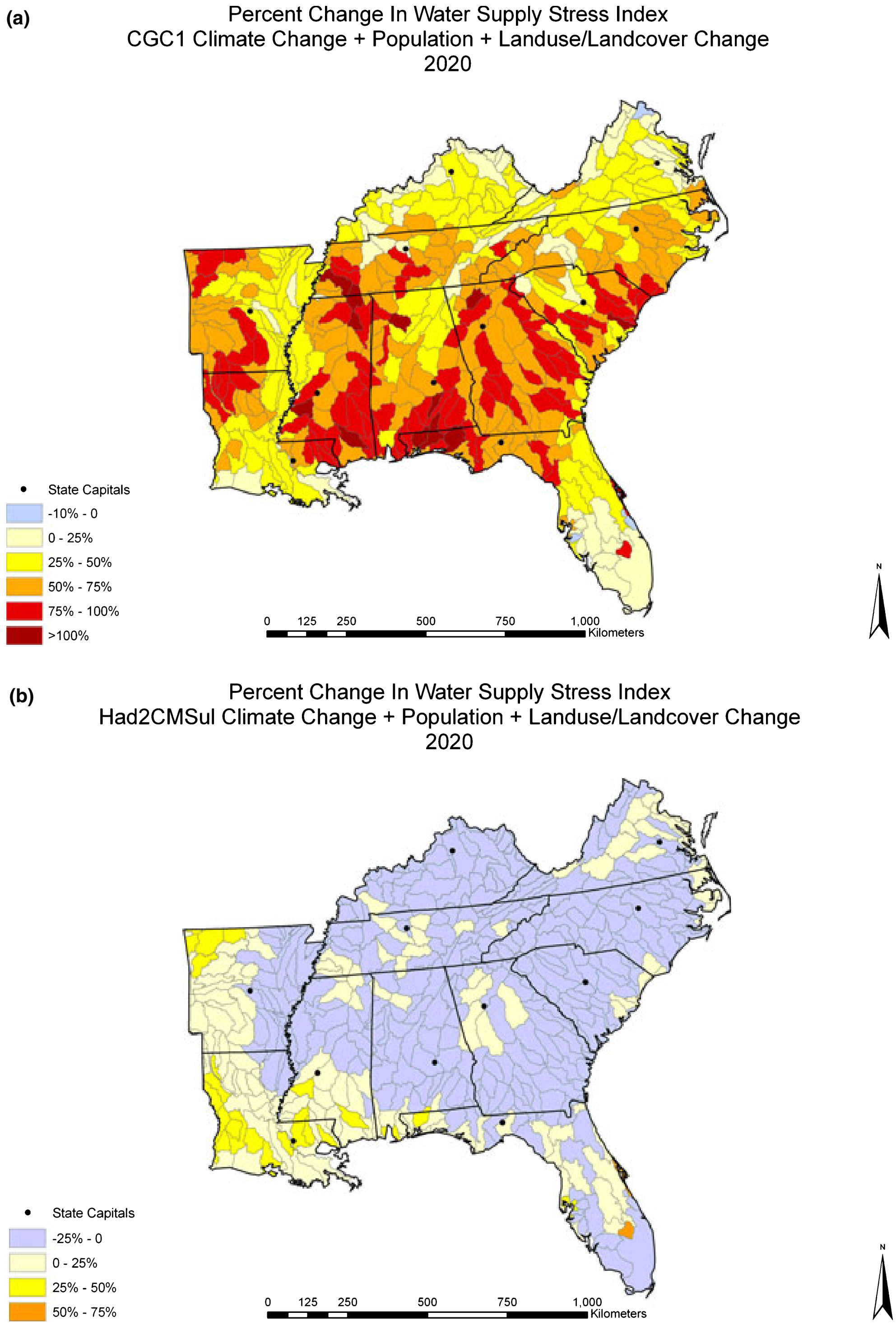

FIGURE 12. Combined Impacts of Future Changes in Climate CGC1 (a) and HadCM2Sul (b), Population, and Land Use (Scenario 6) on Water Supply Stress Index. Two climate change scenarios resulted in distinct water stress trend in 2020.

that receive 10-20% more precipitation still showed increased water stress due to large population growth. Increase in 10-20% of precipitation appeared not to be able to balance the increased water stress due to population growth. As a result, cities projected to have dramatic increase in population and/or a dry climate change scenario had the most severe impacts (up to 98% increase in WaSSI) by 2020 (Table 2). Those cities included Oklahoma, Tallahassee, Raleigh, Jackson, and Austin. Across the region, CGC1 climate change and population change caused an increase in water stress by 48%, which was a more severe effect than the HadCM2Sul and population combination (Table 2) (Figure 7).

Scenario 6: Climate, Population, and Land Use Change Impacts

It was interesting to examine the individual impacts of climate, population, and vegetative cover change on regional water supply and demand, but in reality these changes occur simultaneously. Similar to Scenario 5, the effects of multiple stresses were additive, the end results of the three factors' interactions reflected the sum of positive and negative impacts on WaSSI. Water stress was expected to be relieved somewhat from the land use change perspective because areas of forest and irrigated land were expected to decline in the study region. However, as discussed with Scenario 5, the drier CGC1 climate and population growth reduced water supply and increased WD at a much higher magnitude than the effect of land use change. Therefore, a combination of the three factors generally caused an overall increase in water stress. The warming and drying climate (CGC1) elevated water stress dramatically and canceled the limited water stress relief from land use change. A wetting trend of HadCM2Sul climate change scenario and urbanization reduced water stress in most watersheds in the region, especially east of Mississippi. However, in spite of a wetter climate, some watersheds still showed increased stress mainly due to large increases in population (Figure 12). Consequently, our study showed that the regional WaSSI was expected to increase in western parts of the study region, but to be variable in the eastern part of the region. Overall, land use/land cover change played a minor role in shaping water availability from the point of water quantity, thus its impact on water stress was limited. In contrast, precipitation patterns and population growth had a huge impact on water availability and water stress patterns locally and across the region.

CONCLUSIONS AND FUTURE STUDIES

Water stress is affected by many complex natural and socioeconomic factors, and the spatial and temporal distribution of water stress is difficult to project. New tools are needed for the society to move to adaptive management under the projected climate and global change (Pahl-Wostl, 2007). A new WaSSI model was proposed for assessing future changes in both water supply and demand and their relations across the southeastern U.S. This paper began to explore the potential individual and combined impacts of climate, population, and land use change on water availability, demand, and water stress trends by 2020. Across the southern U.S., changes in climate had the greatest impacts on water stress, followed by population (only locally significant), and land use (which relieved water stress in some instances). Traditionally water stressed areas with little precipitation or regions with large irrigated areas or large water usage from thermoelectric facilities had more stress with increased population and global warming. Less populated areas that had little water shortage problems in the past may also face water stress issues under changes in global and regional climate. However, future changes in precipitation patterns remained uncertain, especially in the eastern U.S., and thus realistic prediction of future water stress remains challenging. The severe drought in 2007 across the study region was the best example that demonstrated how changes in precipitation patterns could cause serious water supply problems. Water resource planning must consider both the uncertainty of water supply due to climate change and continued increase of WD due to population increase.

This work represents the first step to examine watershed-scale water supply and demand simultaneously across a large region. The model we developed can be used as a framework to examine future changes in water stress as induced by humans and nature. Several areas need improvement and should be considered for future studies in modeling water stresses at large scales.

1. We used a rather simple definition for water supply that represents the maximum water availability (streamflow + return flow + deep groundwater withdraw) for total water withdrawal on an annual basis. In actuality, most of the streamflow will discharge to major rivers, and eventually move to the ocean as runoff to meet minimum requirements sustaining stream aquatic ecosystems (i.e., environmental flow). In this case, large amount of water yield is not available for human use. In addition, we did not consider the capacity of water supply systems, such as reservoirs. We plan to use reservoir capacity to determine surface water supply limit for each basin. Furthermore, most watersheds used in this study receive water from upstreams, thus the water supply term should include that component. A more comprehensive definition of the water supply term is needed in future studies.

2. Our current models used long-term average annual climate drivers. Generally, water shortages occur due to a series of unusually low precipitation years, not long-term streamflow deficits. Also, water shortages can occur within a year when WD is highest and water yield is lowest (i.e., summer). Neither annual nor interannual issues are addressed in the present study.
3. The current model compares water supply and demand only within the same eight-digit HUC watershed. In reality, large metropolitan areas seldom draw water exclusively from local basins and most of the HUC receive and discharge water from adjacent watersheds. In many cases (e.g., Los Angeles, Southern California, and New York City, New York) water is transported from great distances, but the current model does not account for this transport and may therefore overpredict local water stress.
4. Water availability is limited by water quality. Land use change was modeled to increase water quantity in this study, but it is likely to reduce water quality. Future assessments and models should consider the impacts of land use change on water quality and the likelihood that this eventually reduces water available for human use.

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