Impacts of Climate Change, Population Growth, Land Use Change, and Groundwater Availability on Water Supply and Demand across the Conterminous U.S.

by

Ge Sun (Research Hydrologist), **Steven G. McNulty** (Research Ecologist), **Jennifer A. Moore Myers** (Resource Information Specialist), and **Erika C. Cohen** (Resource Information Specialist)

Southern Global Change Program
USDA Forest Service
920 Main Campus Dr. Venture II, Suite 300
Raleigh, NC 27606
Email: Ge_Sun@ncsu.edu
http://www.sgcp.ncsu.edu/

ABSTRACT: U.S. water resources have been increasingly stressed by climate change and population growth. Assessment of long-term impacts of projected changes in climate, population, land use and land cover, and groundwater availability on regional water resources is critical to the sustainable development of the U.S. economy. The overall goal of this study was to fully budget annual water availability for water supply (Precipitation – Evapotranspiration + Groundwater supply + Return flow) and water demand from commercial, domestic, industrial, irrigation, livestock, mining, and thermoelectric uses. The Water Supply Stress Index (WaSSI) and Water Supply Stress Index Ratio (WaSSIR) were developed to evaluate water stress conditions over months, years, and decades for 2100 8-digit Hydrologic Unit Code (HUC) basins in the lower 48 states. We integrated a monthly time step water balance model, climate predictions from two Global Circulation Models (i.e., CGC1 and HadCM2Sul), and hypothetical land use, population change, and groundwater availability scenarios to project potential impacts on short- and long-term future water supply stress. We found that a projected increase in population of 50% greatly stressed water supply in metropolitan areas and could cause water shortage problems regardless of climate change. Predicted land use and land cover changes will have little effect on water quantity and water supply-water demand relationships. In contrast, climate change had the most pronounced effects on regional water supply and demand, especially in some western watersheds where water availability is historically low. Watersheds that depend on groundwater are most sensitive to groundwater depletion. The simulation system developed by this study is useful for regional water resource planners to address water shortage problems such as those experienced across the southeastern U.S. in 2007. 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.

INTRODUCTION

Water resources across the United States 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 United States General Accounting Office (GAO) revealed that many western (e.g., Colorado) and eastern (e.g., South Carolina) states, could face significant local or regional water shortages in the years to come. A full picture of water availability and use at the national or local levels is not available because a comprehensive water 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 resource 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 quantify current and future human water demands 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 U.S. population now exceeds 300 million, and it is projected to almost double within the next 50 years. Many of the metropolitan areas are expanding, and population is expected to increase at least 50% in the next 20 years. In addition to an increasing population base, General Circulation Models (GCMs) predict that the U.S. will experience significant increases in air temperature and variability of precipitation associated with global warming (Kittel et al., 1997). The National Assessment on Climate Change Impacts suggests climate change will likely increase precipitation intensity, variability, and form (i.e., more rainfall than snow). Climate warming is likely to effect snow melt and reduce snow pack, thus altering streamflow patterns in the western U.S. Climate change not only disrupts many aspects of natural ecosystems, it also negatively impacts regional economies. For example, as the U.S. warms, the amount of water withdrawn for crop irrigation is expected to increase (with an associated increase in production costs) as precipitation decreases and evapotranspiration increases (Peterson and Keller, 1990; Doll, 2002).

In addition to climate and population changes, land use patterns have and will continue to change dramatically over the next 20 to 40 years. For example, the total urban area in the southern U.S. has increased more than 200% from 1945 to 1992. Although total forest area did not change much in the past decade, large areas of land in the same parts of the region (e.g., Florida, the piedmont region of North Carolina) have been converted to urban areas, while agricultural areas in the lower Gulf coastal plains have been reforested (Wear, 2002). The combination of these factors may predispose some regions to water resource changes in the coming decades.

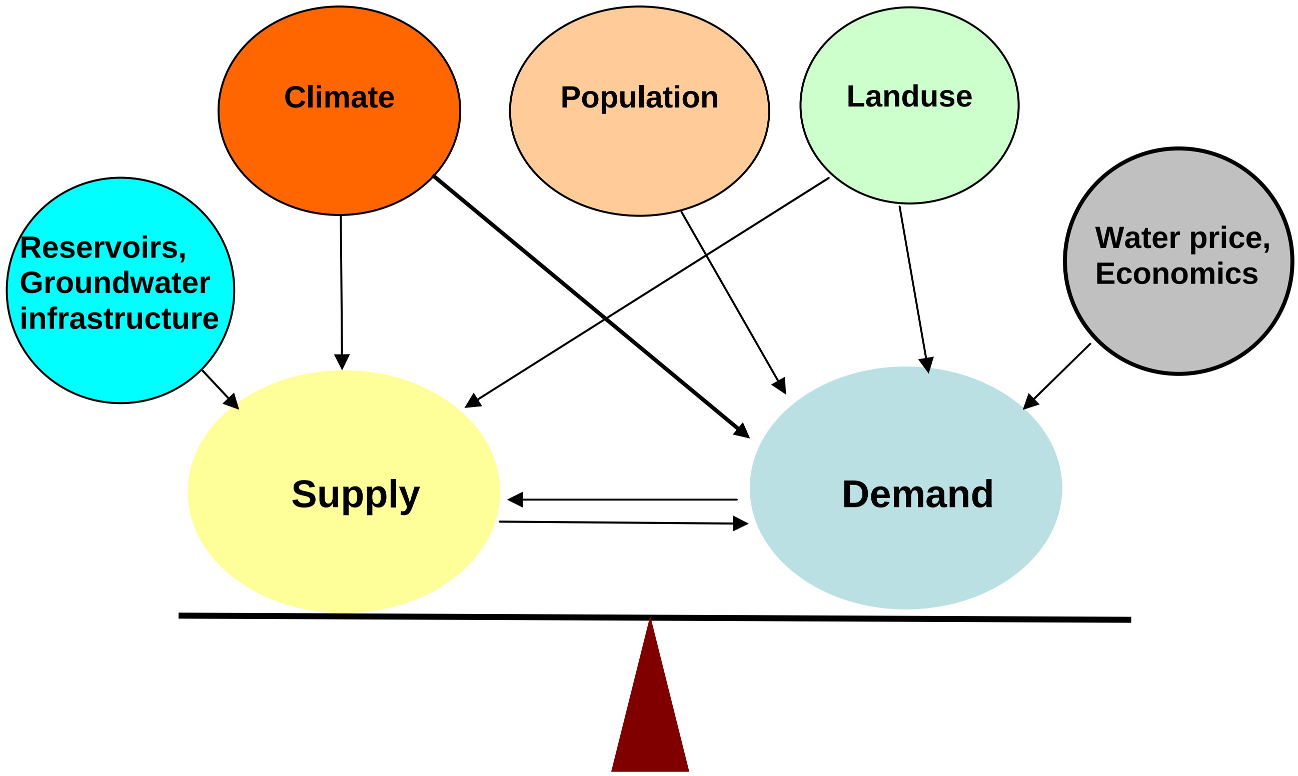


Figure 1. Factors affecting water supply and demand and their relations.

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 hydrologic models are designed to work at different spatial and temporal scales and are not designed to assess 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 treat 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 US using the HUMUS hydrologic model, and later the model was used (Brown et al., 1999; Thomas et al., 2003) to examine how global climate (including atmospheric CO_2 and El Nino/Southern Oscillation) impacts 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. Using historic USGS water use data, Brown (2000) projected fresh water withdrawals for the next 40 years for seven economic sectors including livestock, domestic, public, industrial, 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 (WRRs), which were considered rather coarse for use by local water managers. Roy et al. (2005) projected water withdrawals at a much finer scale (i.e., county level) across the U.S. from 2000 to 2025 by combining an extrapolation of historic water use trends (Solley et al., 1998; Hutson et al., 2004) with two projections of energy use, population growth, and water use efficiency. This study did not compute the full water budget (e.g., actual evapotranspiration losses) and thus was of limited use in projecting water supply and demand relationships. Roy et al. (2005) recommended an improved national comprehensive water sustainability assessment with finer spatial resolution that included the effects of in-stream ecosystem water use and climate change impacts on water availability.

Our research attempts to address some of the research gaps in previous continental scale water resource studies by: 1) developing an integrated modeling approach that combines an annual water yield model with climate, land use and land cover, and population change projections to assess water supply stress that reflects water supply and water use by multiple users; and 2) applying the modeling system to project water stress over the next 30 years under different scenarios of climate, forest management, population growth, and groundwater availability.

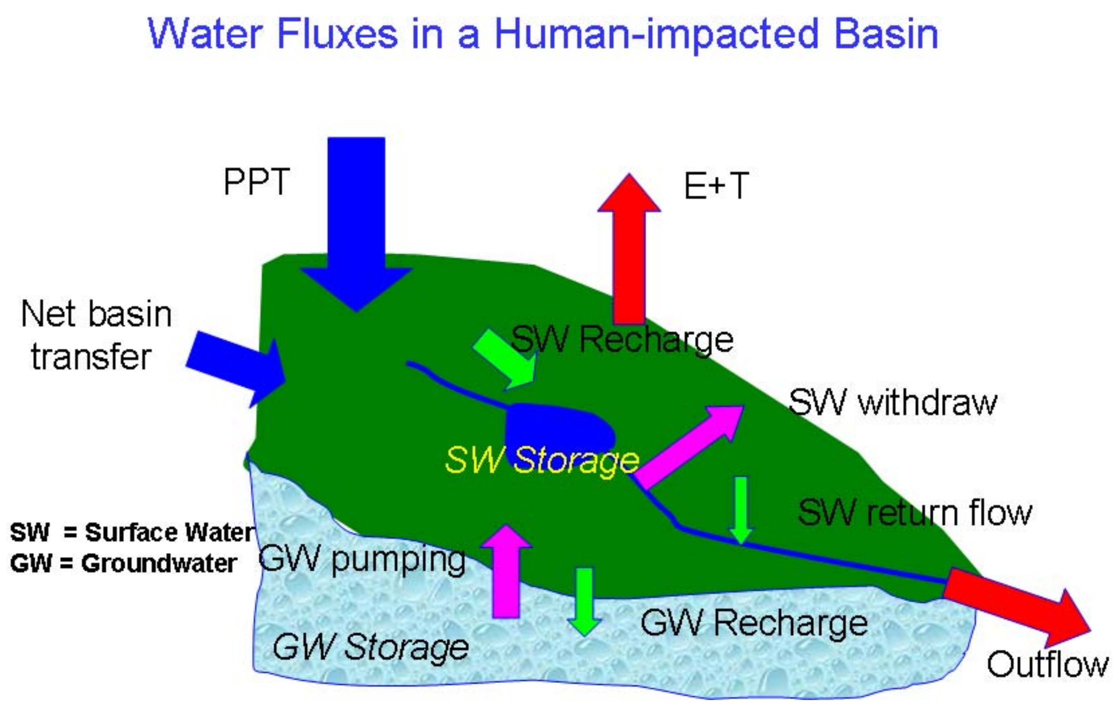


Figure 2. Schematic of water flows and storage in a human-impacted basin.

METHODS

The guideline for a full accounting of both water supply and water use components was the water budget of a human-impacted basin as shown in Figure 2. In this study, we used the U.S. Geologic Survey (USGS) 8-digit Hydrologic Unit Code (HUC) watershed as the working scale. There are approximately 2100 8-digit HUC watersheds in the lower 48 U.S. The database included historic water use and return flow rates by water use sectors, groundwater withdrawal, historic and projected climate, population, and land use. The individual databases had different temporal and spatial scales; all were scaled to the 8-digit HUC watershed level for hydrologic simulation and water stress computation. Once databases were assembled, scenarios were developed to individually and collectively quantify the impacts of climate, land use, and population changes on water supply and demand.

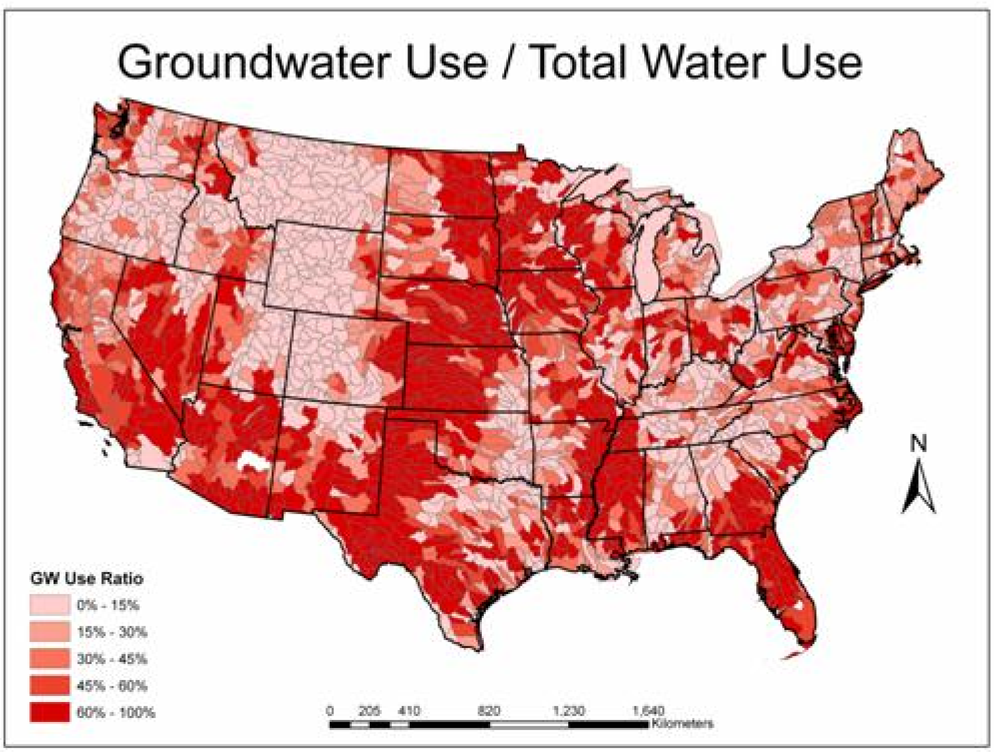


Figure 3. Distribution of groundwater withdrawal relative to total water withdrawal by 8-digit Hydrologic Unit Code.

Historic Water Withdrawals and Use

The 1995 and 2000 national anthropogenic water use survey datasets published by the USGS were used to determine historic water demand. Overall, the two survey periods recorded similar water use (Solley et al., 1998; Hutson et al., 2004; Roy et al., 2005). Therefore, we used 1995 datasets as our baseline for comparison with alternative change scenarios. The USGS water survey grouped water users into one of 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 eastern U.S. (east of the Mississippi River), thermoelectric water withdrawal dominates (74% of all use), followed by irrigation centered in the Mississippi valley and western Texas regions. However, because the return flow rates from power plants are high (> 90%), irrigation is the largest sector in terms of consumptive (i.e., water that is withdrawn and not shortly thereafter returned to the ecosystem) water use (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. In the western U.S. (west of the Mississippi River), over 80% water withdrawal is used for irrigation, and about 14% is for thermoelectric use. Consequently, the western U.S. has a much higher water consumptive use ratio in the agricultural irrigation sector as compared to the eastern U.S. The central and coastal U.S. regions rely heavily on groundwater as a primary water source (Figure 3).

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^o by 0.5^o (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 for all 13 southern states. Then, the gridded climate datasets were overlaid on 8-digit HUC watersheds. Air temperature and precipitation data that drive the evapotranspiration and water balance models are described later.

Global Circulation Models are becoming more reliable at replicating historic climate, and therefore, confidence in these models' ability to forecast future climatic conditions has grown (Stott et al., 2000). Two future climate change scenarios (Kittel et al., 1997) were acquired from predictions by the HadCM2Sul model, developed by the UK 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 (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 areas west of the

Mississippi River will experience a decrease in annual 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 annual precipitation and a larger increase in average annual air temperature (1^o to 2.5^oC) in northern parts of the country by 2020 (Figure 4).

Historic and Projected Population Data

The U.S. Census Bureau records indicate that population increased about 30% during the past 20 years (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 8-digit HUC watershed scale 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 U.S. total population was predicted to increase by 41%, and 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 decrease of 10% in parts of the Midwest, to over +150% in the southeastern U.S., Nevada, and southern California when compared to 1995 levels (Figure 5). 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 5).

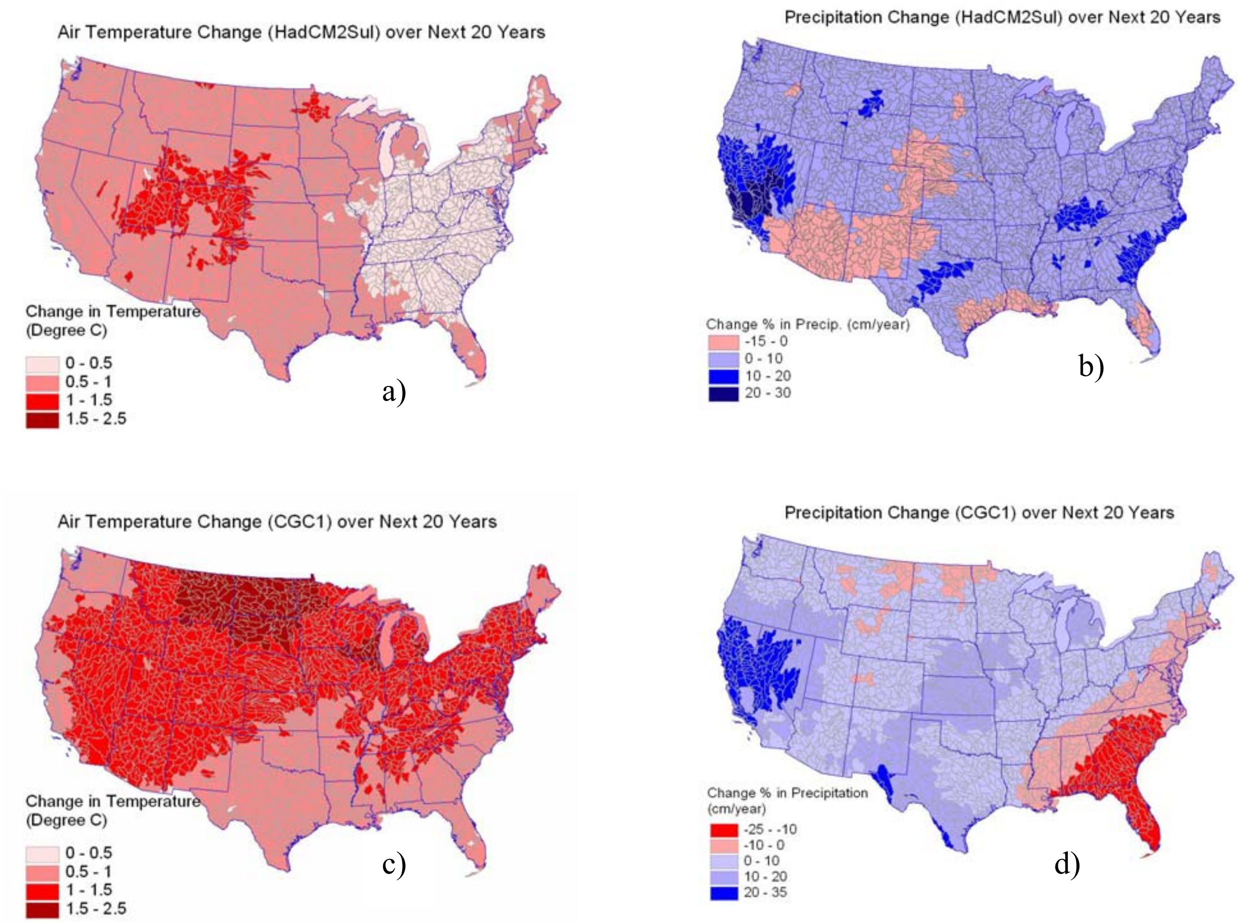


Figure 4. Predicted changes in air temperature and precipitation across the U.S. by the CGC1 model (a and b) and the HadCM2Sul model(c and d) in 2020.

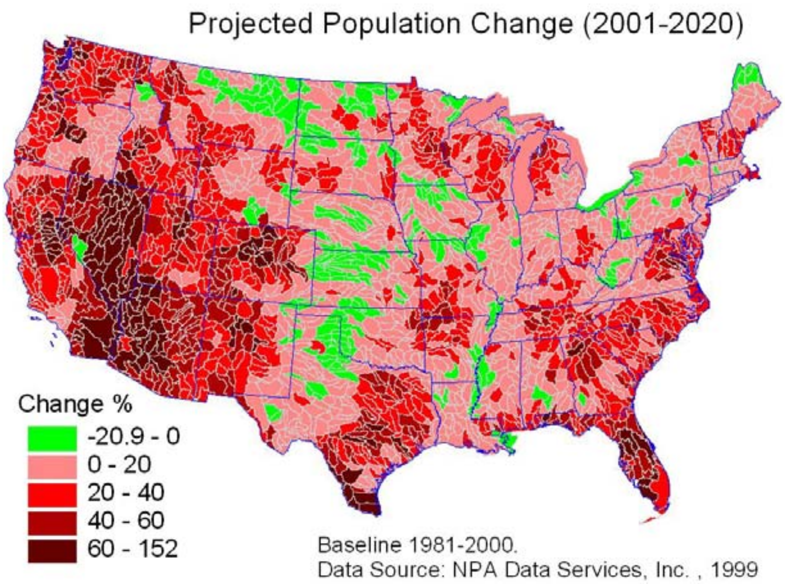


Figure 5. Projected changes in population during the next 20 years.

Historic and Projected Land Use Change

The 1992 National Land Cover Dataset (NLCD) (http://edc.usgs.gov/glis/hyper/guide/mrlc) has a 30-m spatial resolution and was used for the land use and land cover baseline. All land use and land cover classes were aggregated into five major categories according to their hydrologic properties. These include forests (i.e., conifers or hardwoods), croplands, urban/residential, and water bodies. Land use is a major driver for the hydrologic model estimates of watershed scale evapotranspiration (as described in the next section). Land use change at the county-level from the 2002 baseline to 2032 were projected using a county-level econometric model (Lubowski, 2002). 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 (Plantinga et al., 2007).

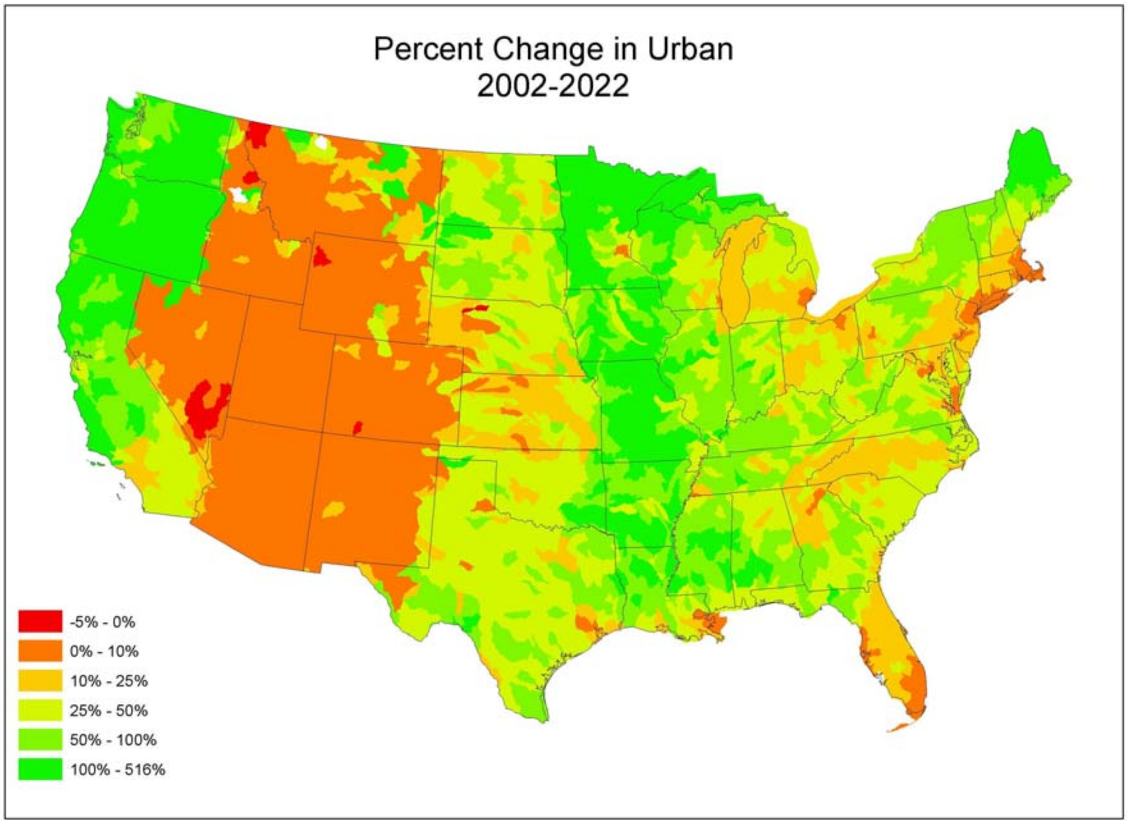


Figure 6. Projected changes in urban land areas in the next 20 years.

The land use projections that were scaled up to the HUC level suggest that urbanization dominates land use change patterns. Urban areas will increase from 34.2 million hectares in 2002 to 47.8 millions hectares by 2022. Urban areas are expected to increase by 40% on average but range from no increase to increases of more than 1000% (Figure 6). Pasture and Conservation Reserve Program land areas will decrease by 12% and 22%, respectively. Forest and crop lands may decrease only slightly, but the change is not uniform at the 8-digit HUC watershed scale.

Land use change data provided by Plantinga et al. (2007) does not include any federal lands and excludes some landcover types (e.g., water bodies, roads, barren lands), so those land use and land cover types were derived from the 1992 MRLC data, aggregated to the 8-digit HUC watershed scale, and then added to the Plantinga land use dataset.

This study assumed that the proportion of irrigated lands would not change over time, because the land use model did not predict changes in irrigated lands. However, total irrigated land area may potentially change due to changes in urbanization.

Definitions of Water Supply, Demand, and Stress Index

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

$$WS = SS + GS + \sum RF_i$$

Where,

WS = Total water supply volume (m^3) for each 8-digit HUC watershed.

SS = Total surface water supply for each 8-digit HUC watershed. SS is estimated at the monthly time scale using a water balance model (Zhou et al., 2008). This hydrological model predicts water yield at the HUC level as a function of monthly potential evapotranspiration, land use type, canopy interception capacity, plant rooting depth, soil moisture content, and precipitation received.

GS = Total groundwater supply as represented by USGS annual historic (1995) groundwater withdrawal records (Solley et al., 1998).

RF = 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 historic (i.e., 1995) (Solley et al., 1998) return flow rate (RFR) multiplied by the water use (WU). Return flow rates vary among watersheds and water use sectors. For example, RFR for the domestic use sector averages 67%, and the thermoelectric sector has a RFR higher rate (>70%), while most of the watersheds have RFR greater than 90%.

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

$$WD = \sum WU_i + \sum PB_i \qquad i = 1\text{-}7$$

Given these relationships, we proposed two new hydrologic terms; the Water Supply Stress Index (WaSSI) (Equation 1), and the Water Supply Stress Index Ratio (WaSSIR) (Equation 2). The term WaSSI is used to quantitatively assess the relative magnitude of water supply and demand at the 8-digit HUC watershed level. The term WaSSIR is used to assess the relative change in WaSSI between the baseline scenario (x = 1) and one of the future scenarios (x = 2 through 6) as described in next section. A positive WaSSIR value indicates increased water stress and a negative WaSSIR indicates reduced water stress when compared to historic water stress conditions (Scenario 1):

$$WaSSI_x = \frac{WD_x}{WS_x} \qquad (1)$$

and

$$WaSSIR_x = \frac{WaSSI_x - WaSSI_1}{WaSSI_1} \qquad (2)$$

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

We focused on three major water use sectors (i.e., domestic, irrigation, and thermoelectric plants) to predict future water demand. Changes in water uses affect the total water supply due to the return flow component of WS. Water demand for domestic water use is predicted by correlating USGS historic water use (million gallons per day) in the domestic sector with population (in thousand persons) for 1995 at the 8-digit HUC watershed level (0.05 significance level) .

Water use in the domestic sector = 0.114 × Population $r^2 = 0.95$, n=666 (3)

Similarly, water demand for irrigation is predicted by correlating USGS historic water use (million gallons per day) in the irrigation sector with the irrigation area (in thousand acres) for 1995 at the 8-digit HUC level.

Water use by irrigation = 1.3714 × Irrigation Area + 2.07 $r^2 = 0.67$, n = 666 (4)

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

Water use by the thermoelectric sector = Population × (total electricity in kilowatt-hours use per person) × percentage of electricity generated by thermoelectric plants over total electricity × water withdrawal per kilowatt-hours of electricity generated by thermoelectric plants (5)

Total electrical water use is therefore a function of the amount of thermoelectric and hydroelectric power generated. Water use efficiency by power plants has been increasing since the 1960s, so we assumed future water use per kilowatt-hour would 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 from years 1995 and 2000 suggested little change in water use for the smaller sectors. Therefore, future water use by the other four sectors (i.e., 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 water demand.

Once annual values of water use are determined, a monthly function is applied to redistribute annual water use to each month across the 18 water resource regions. Currently, such monthly redistribution schemes are only applied to the irrigation and domestic sectors. One example is presented in Figure 7. We used state-wide water use data to derive the monthly water use functions.

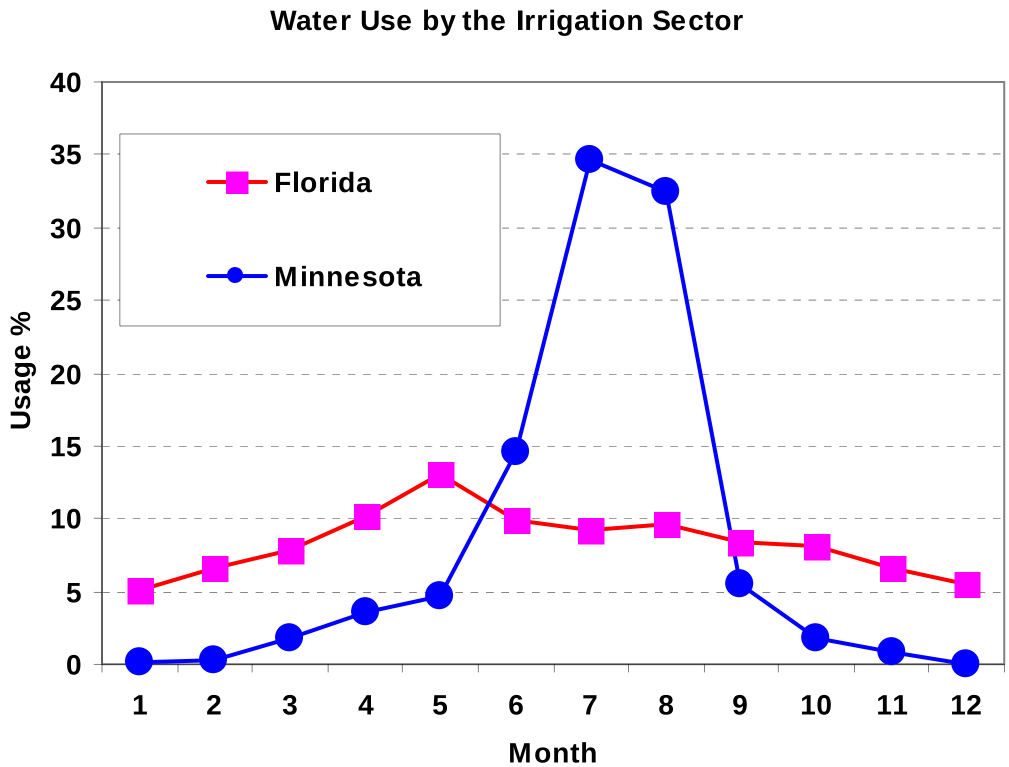


Figure 7. Seasonal water use distribution showing a variable water demand in the North but a uniform pattern for the South.

Classification of WaSSI for Comparison of Water Stress Severity

The WaSSI represents the relative magnitude of water demand and water availability for a particular HUC watershed in any month. Annual WaSSI is generally much smaller than 1.0 in water rich regions, such as the eastern and the Pacific Northwest regions. A WaSSI equal to 1.0 means that water use is reached the maximum water availability. When it is higher than 1.0, water use exceeds water availability, so there must be other water sources from adjacent watersheds available for water transfer.

However, the WaSSI values should not be used to directly compare water stress severity among HUCs, especially between dry and wet regions. For example, the historically dry western U.S. has always had higher WaSSI values than the eastern U.S., but the western U.S. has not consistently had more severe water shortage problems. Water shortage crises for certain watersheds are relative to the watershed's historic patterns of water supply and demand. Therefore, we normalized the WaSSI for each HUC using its frequency distribution over the past 100 years. Similar to the National Drought Monitor classification, we classified the WaSSI into six categories to represent six levels of water stress as a function of both natural and human influences. The six classes are:

1. Normal Conditions: >30-100% percentile
2. D0 Abnormally Stressed: 20-30%
3. D1 Moderate: 10-20%
4. D2 Severe: 5-10%
5. D3 Extreme: 2-5 %
6. D4 Exceptional: 0-2%

Figure 8 provides one example of how often these six water stress categories occur for watershed HUC 3020201 in North Carolina. In this example, the highest WaSSI is about 0.065, lowest about 0.014.

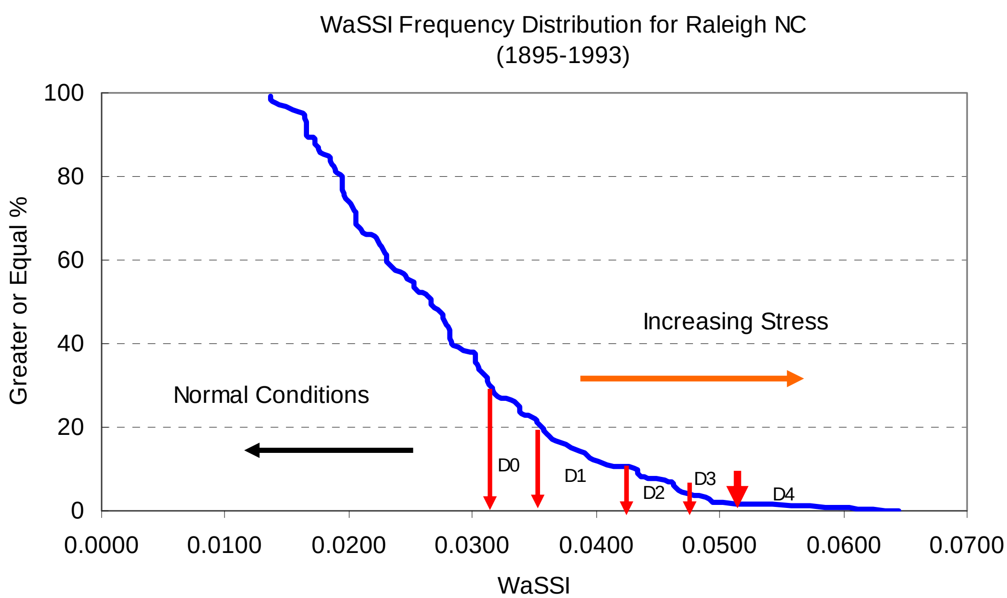


Figure 8. Frequency distribution of estimated WaSSI and water stress classification scheme for HUC 3020201.

Simulation Scenarios

Various hypothetical scenarios were developed to study how historic or projected changes in climate, population, and land use either individually, or in combination, impacted the WaSSI. Sun et al. (2008) examined six scenarios to study the individual (i.e., climate change, population, land use change) and combined factors that affect water stress in the southern U.S. This paper presents six simplified scenarios (Table 1) that extend the previous studies by Sun et al. (2008) from the South to the conterminous U.S. These scenarios compare the magnitudes of water stress response to multiple stressors.

Scenario #1 represented average historic (i.e., 1985-1993) climate, population distribution (1990), and land cover conditions (1992). Calculations of water supply and water demand 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 change (i.e., HadCM2Sul and CGC1 GCMs) impacts on water supply, water demand, and stress indices (WaSSI and WaSSIR) by 2020 without population or land use changes. Scenario #3 was designed to examine if a 20% decrease in forest cover would significantly reduce water stress at a regional scale. Similarly, Scenario #4 examined the effects of reducing irrigation by 20%. Reducing irrigation was presumed to be a viable option for reducing water stress. Scenario #4 examined how a uniform human population increase of 50% would affect water stress. Population change will mainly affect total water demand, in both the domestic and thermoelectric water use sectors. Scenario #5 examined the extreme condition of eliminating groundwater inputs to the water supply to simulate the impact of an exhausted ground water reserve and future climate. Scenario #6 represents a very likely scenario of 50% population increase and future GCM climate scenarios.

Table 1. Modeling Scenarios as Combinations of Climate, Landuse, Population, and Groundwater Availability

Scenario and Land Cover	Groundwater Availability	Land Use/Land Cover	Climate	Population
1: Baseline	1995 level	1992 MRLC	Historic Data (1985-1993)	1990 Census
2: Climate Change	1995 level	1992 MRLC	GCM Projections (HadCM2Sul and CGC1)	1990 Census
3: Land Use Change (Deforestation)	1995 level	Forest area decreased 20% from baseline	Historic Data	1990 Census
4: Land Use Change (Irrigation reduction)	1995 level	Reduce irrigated lands by 20%	Historic Data	1990 Census
5: Groundwater Availability Change	No groundwater	1992 MRLC	GCM Projections	1990 Census
6: Population Growth	1995 level	1992 MRLC	GCM Projections	Increase by 50%

Table 2. Historic Annual Water Supply Stress Index (WaSSI) and Change (WaSSIR) under Climate Change Stresses for Selected Watersheds across the U.S.

Capital city, State, and Hydrologic Unit Code number (HUC)	Scenario 1: Baseline (WaSSI)	Scenario 2: Climate Change (WaSSIR) Negative: Decrease water stress Positive: Increase water stress	
		CGC1	Had2CMSul
2050305 Harrisburg, PA	0.13	11%	-6%
3020201 Raleigh, NC	0.10	38%	-38%
3070103 Atlanta, GA	0.13	40%	-3%
4050004 Lansing, MI	0.17	-8%	-27%
8070202 Baton Rouge, LA	0.26	2%	-13%
10190003 Denver, CO	1.13	8%	-8%
12090205 Austin, TX	0.63	-19%	3%
13020201 Santa Fe, NM	0.53	-21%	-7%
17110016 Olympia, WA	0.03	-1%	-7%
18020109 Sacramento, CA	0.92	-17%	-8%

RESULTS AND DISCUSSION

Scenario 1: Baseline Scenario

Water availability at the monthly and annual scale is controlled by precipitation and actual evapotranspiration (ET). Evapotranspiration is largely constrained by potential evapotranspiration, precipitation, and vegetation water use efficiency (Sun et al., 2005).

The combined complex spatial and temporal patterns of precipitation, ET, and topography resulted in a complex pattern of water availability at the continental scale.

Irrigation and thermoelectric sectors were the two largest water users followed by domestic-livestock and industrial users. Consequently, the western region had the highest water supply stress index (WaSSI). Several isolated watersheds in the eastern region also showed high water stress, primarily due to high thermoelectric water demand (Figure 9).

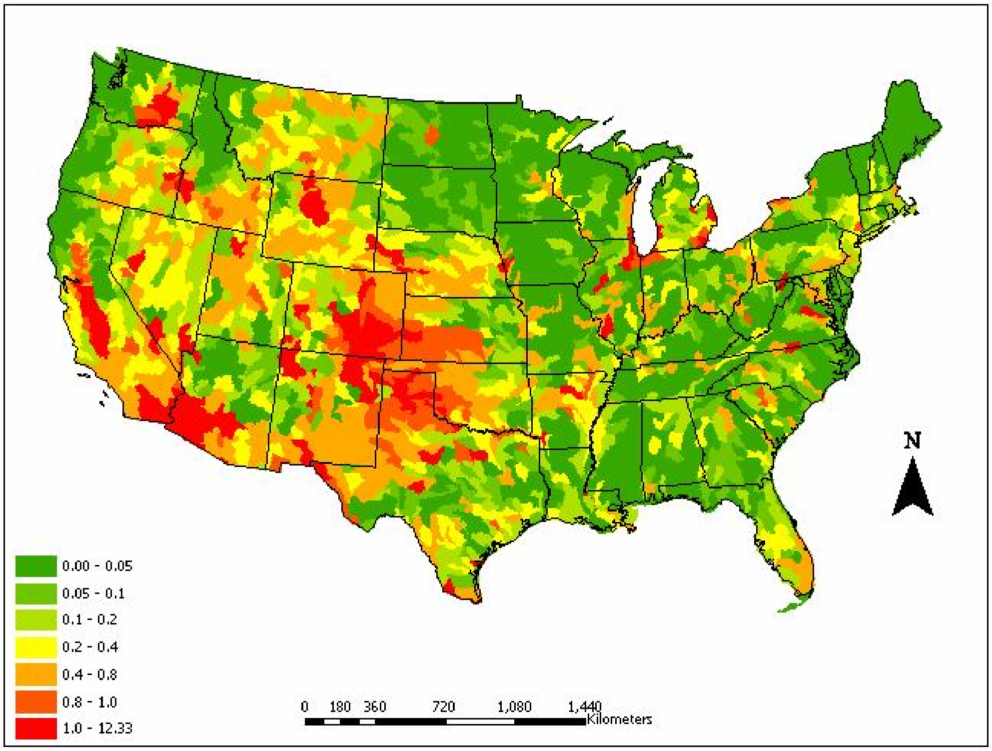
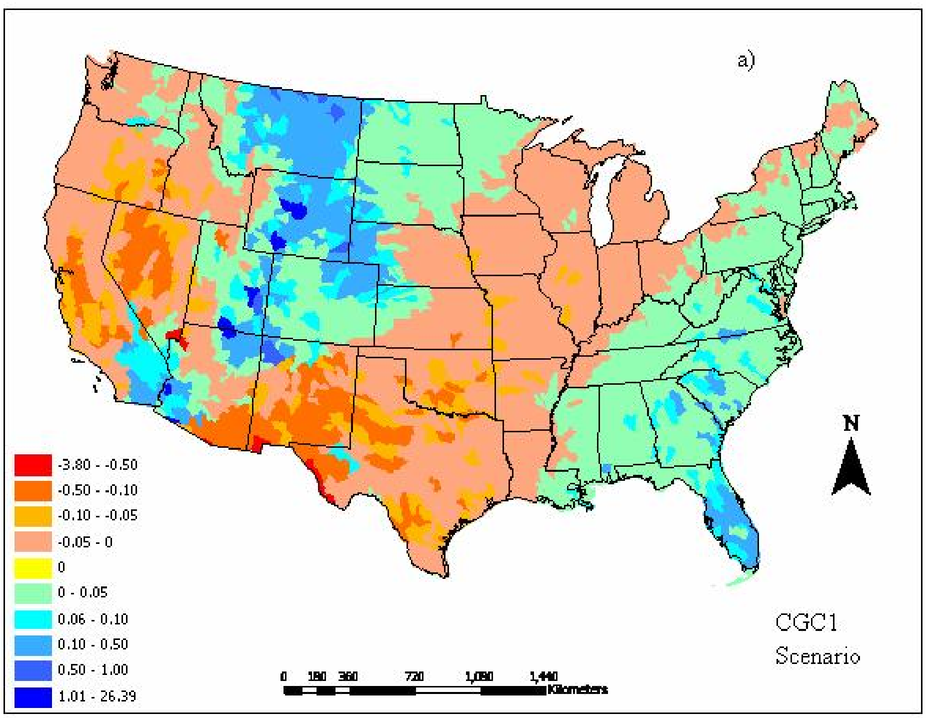


Figure 9 Historical Average (1895-1993) Annual Water Supply Stress Index (WaSSI) across the 2100 8-digit HUC watersheds.

We selected capital cities to illustrate local WaSSi impacts. Denver and Sacramento had the highest and second highest WaSSI values of 1.13 and 0.92, respectively, followed by Santa Fe and Austin (Table 2). Those cities experienced high water supply stress due to low water availability and high water demand from large populations (e.g., Baton Rouge and Atlanta). The national weighted average WaSSI of 0.6 (Figure 7) was much lower than the predicted WaSSI for selected large cities in the West, but much higher than those in the East, suggesting more complex water stress patterns at the continental scale. Human population was only one of the driving factors that caused water stress. In many cases, population played only a minor role in the overall water stress since domestic water use was only a small portion of the total (<15%) in many watersheds (Solley et al., 1998). Other factors affecting both water supply and demand should be included to have a comprehensive balanced water stress assessment.

Scenario 2: Climate Change Impacts

Annual precipitation and evapotranspiration in 2020 were projected to either slightly increase or decrease dramatically depending on the GCM used, compared to historic (i.e., 1895-1993) hydrologic conditions. In the east, model 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 scenario 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 upland regions with generally higher runoff than the coastal zones. As a result, the WaSSI values increased under the CGC1 scenario but decreased under the under the HadCM2Sul scenario for the eastern U.S. (Figure 10). 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.



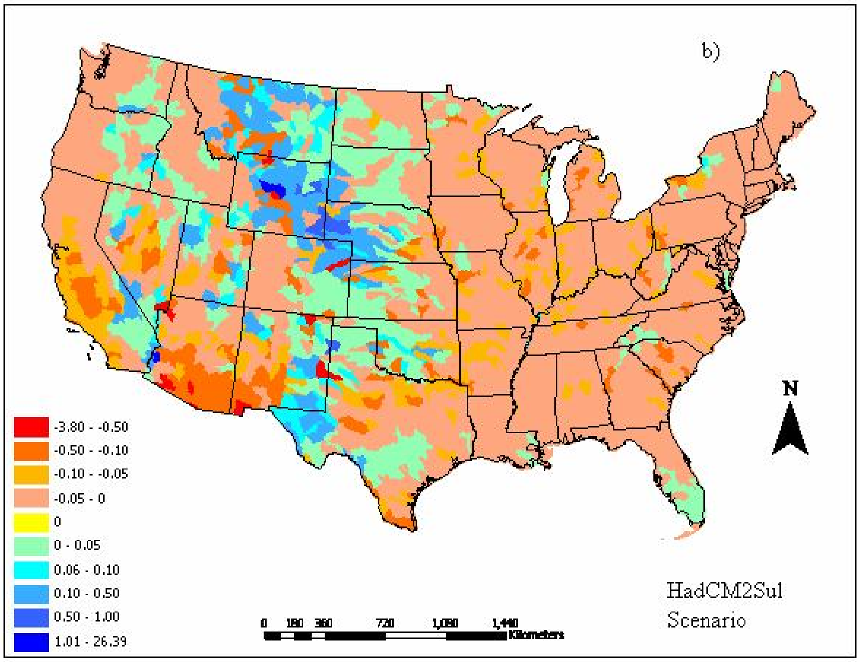


Figure 10. Effect of Climate Change on Average Annual Water Stress Index during the Next 30 years under the CGC1 Scenario (10a), and the HadCM2Sul Scenario (10b). Positive values represent an increase in water stress and negative values represent a decrease.

Among the 10 selected capital cities and under the HadCM2Sul 'wet' climate change scenario, most of the cities showed reduced water stress. Some historically high water stress cities such as Lansing and Raleigh may benefit from climate change in terms of water stress. However, some cities such as Austin may experience increased water stress. Under the CGC1 scenario, most cities in the eastern U.S. had a large increase in water stress, while most in the western U.S. showed a decrease in water stress. However, water stress in Denver was projected to increase.

As a whole, average water stress was predicted to decrease slightly (<10%) under the CGC1 climate scenario, and the decrease was large (>100%) under the HadCM2Sul climate scenario (Figure 10). As in other impact studies (Jha et al., 2006), the two GCMs predicted different future precipitation patterns for parts the study region, resulting in different hydrologic conditions and distinctly different water stress patterns. Reducing the uncertainty in climate predictions at the watershed to regional scale is needed for future impact assessment studies to provide a realistic forecast of water stress to resource managers.

Scenario 3: Land Use Change Impacts: Deforestation by 20%

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. World-wide, small watershed scale forest manipulation experiments have documented that deforestation (i.e., converting from forests to agricultural or urban uses) generally increases water yield due to a reduction of total forest evapotranspiration (Sun et al., 2005). As expected, a uniform of reduction of 20% of forest area in each HUC resulted in an increase in water yield.

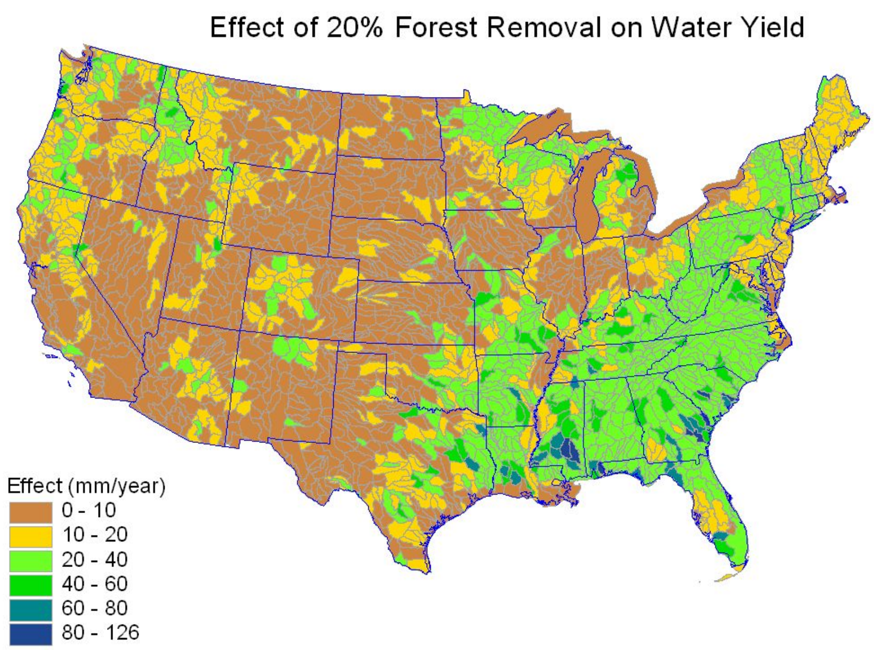


Figure 11. Effects of Forest Removal on Average Annual Water Yield.

The highest absolute increase in water yield (in mm/year) was found in the eastern U.S. (Figure 11), but relative water yield increase was found in the dry regions west of the Mississippi River. This increase in water yield is translated to a decrease in WaSSI, mostly in the dry regions.

Scenario 4: Land Use Change Impacts: Irrigation Reduction by 20%

The reduction in irrigation land area (and subsequent reductions in water use) directly resulted in decreased in total water demand, and thus reduced water stress. The effect of this scenario was most significant in watersheds where irrigation water use comprised a large proportion in the total water demand, such as the California valley, northern Taxes, and the Mississippi Valley.

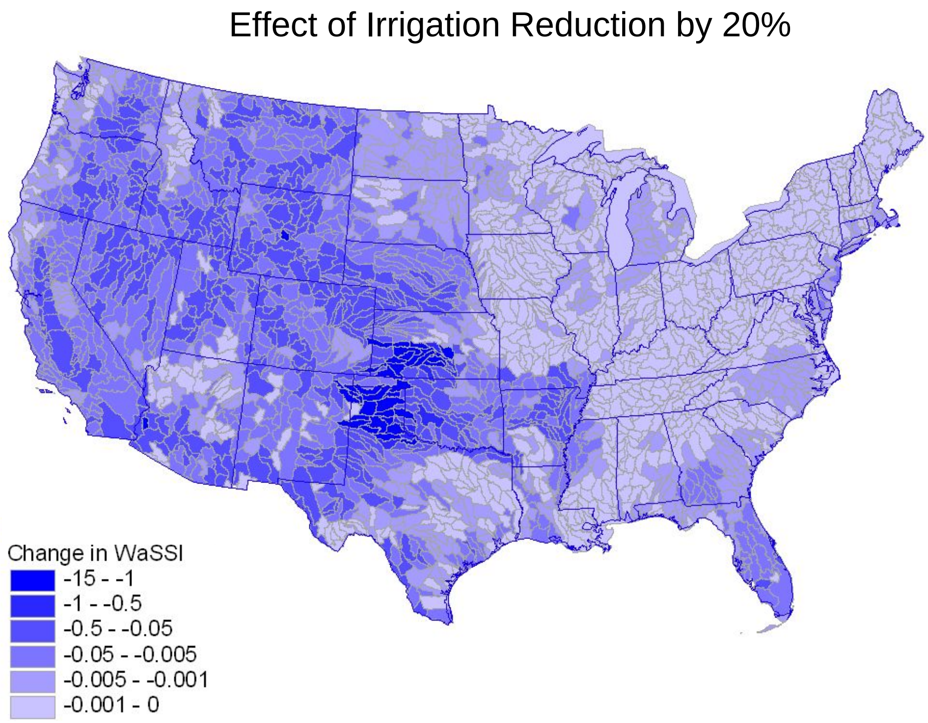


Figure 12. Effects of a Uniform Reduction in Water Use by Irrigation by 20% on Water Stress.

Scenario 5: Impacts of Groundwater Availability: No Groundwater Supply

Once groundwater is exhausted, water stress is expected to increase dramatically in areas that depend on groundwater as a significant component of their total water supply. Those areas include southern California, Nevada, New Mexico, the border between northern Texas and Nebraska, and isolated areas in theeastern U.S, most notably the Mississippi Valley and southern Florida.

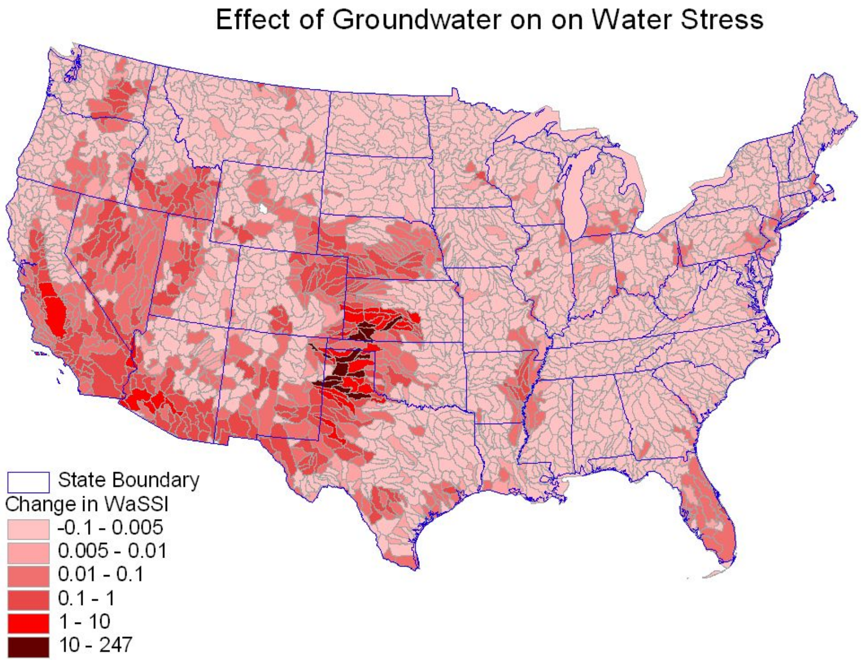


Figure 13. Effects of Groundwater Depletion on Water Stress.

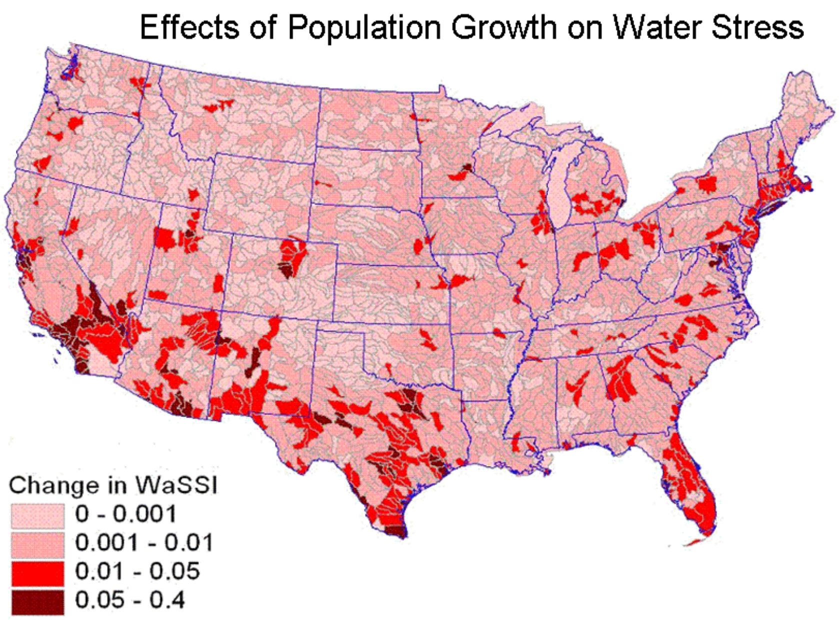


Figure 14. Effects of a Uniform Increase in Population Growth of 50% on Water Stress.

Scenario 6: Impacts of Population Growth

The amount of water demanded by the domestic and thermoelectric water use sectors was directly related to population growth (see Equations 3 and 5). As expected, a large increase in water demand and little increase in water supply resulted in an increased WaSSI overall. Therefore, population centers that were traditionally under high water stress due to large domestic water use were predicted to experience even more water stress with further population growth (Figure 14).

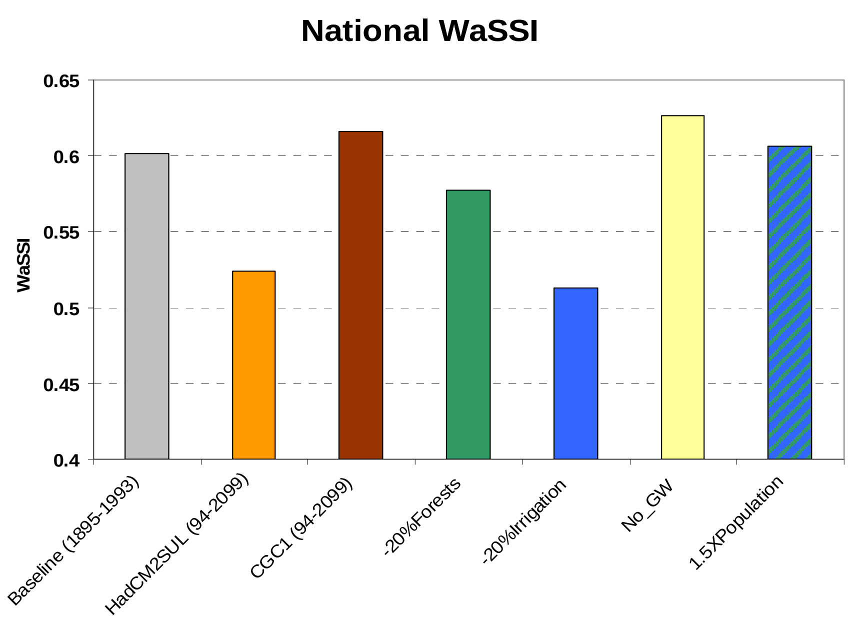


Figure 15. Summary of Annual Long-term Averaged Water Stress Index under the Six Hypothetical Scenarios.

Comparisons among All Scenarios at the Annual and Monthly Scale

The annual, continental, long-term average WaSSI was estimated to be approximately 0.6. The climate change (CGC1) and population growth scenarios resulted in a slight increase of overall WaSSI. Reduction of irrigation water use by 20% or the climate change (HadCM2Sul) scenarios could greatly reduce water stress while forest removal by 20% could reduce WaSSI slightly.

However, it should be noted that this continental average has limited use since the water stress has large spatial variability across the 2100 HUC watersheds. In addition, long-term annual average WaSSI is not very informative since water stress occurred locally on a seasonal basis. As illustrated in Figure 16, on average, the summer months (i.e., July-September) had the highest water stress. A wetter climate change (HadCM2Sul) could greatly reduce overall water stress, and water management (such as reducing irrigation) could achieve a similar goal. Groundwater depletion will have the most severe impact on water stress during the summer months when water demand is the highest.

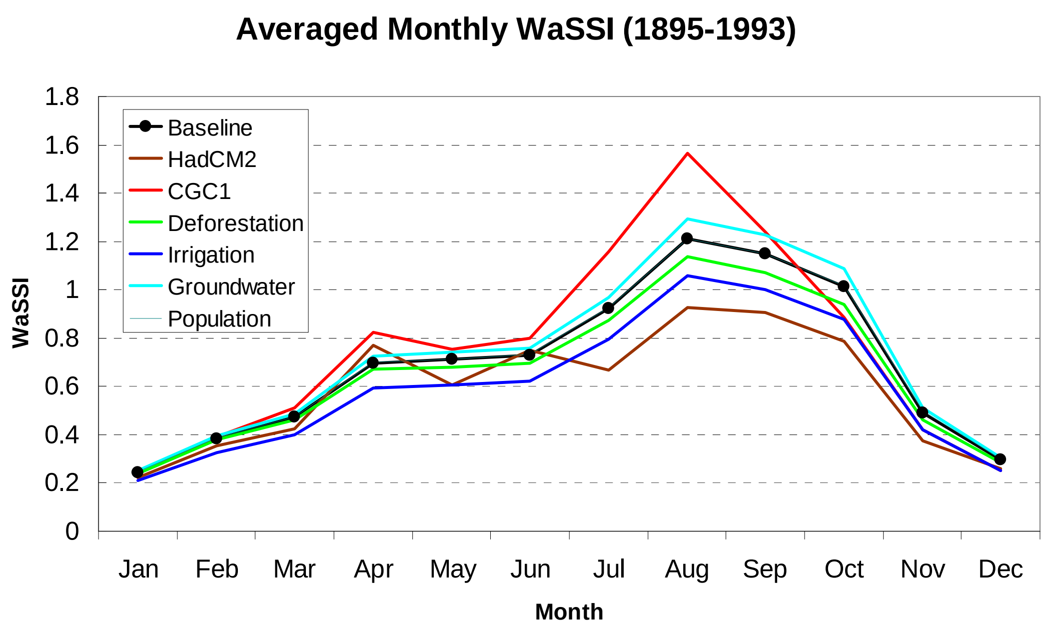


Figure 16. Comparison of Long-Term Averaged Monthly WaSSI of the Continental U.S.

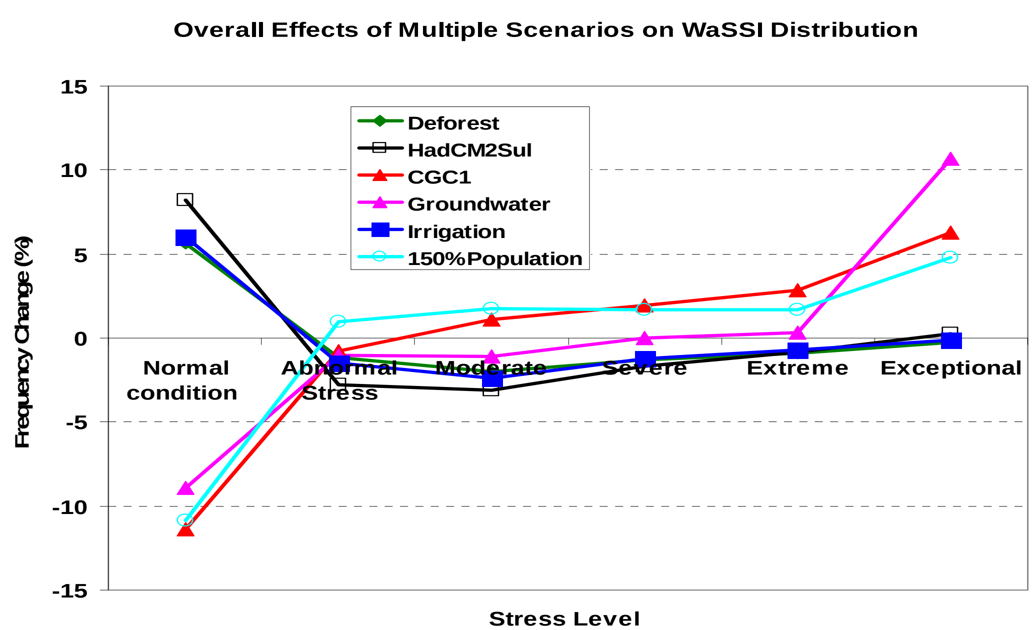


Figure 17. Comparison of Long-Term Impacts of Six Hypothetical Scenarios on the Frequency Change of the Six Water Stress Index Categories.

CONCLUSIONS AND FUTURE RECOMMENDATIONS

Water supply stress is affected by many complex natural and socioeconomic factors, and the spatial and temporal distribution of water stress is difficult to project under a changing climate. New tools are needed for society to move to adaptive management under the projected global change environment (Pahl-Wostl, 2007). Our traditional assumptions and policies on water resource management may not be valid as warned by the U.S. Geological Survey (Milly et al., 2008).

This study proposed a new water supply stress index (WaSSI) for assessing future changes in both water supply and demand and their relations across the U.S. This work began to explore the potential individual and combined impacts of climate, population, groundwater availability, and land management options on water availability, demand, and water stress. Across the continental U.S., changes in climate had the greatest impacts on water stress, followed by population (only locally significant), and land management (which relieved water stress in some instances). Traditionally, water-stressed areas with little precipitation, regions with large irrigated areas, and thermoelectric facilities with large water usage had more stress with increased population and global warming. Less populated areas with few water shortage problems historically 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 predictions of future water stress remain challenging. The severe drought of 2007 across the southeastern region was a good example of 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 water demand due to population growth.

This work represents the first step towards examining watershed–scale water supply and demand simultaneously for the conterminous U.S. Several areas need improvement and should be considered for future studies in modeling water stresses at large extents. These include: 1) the interaction of water flow from and to watersheds (ignored in this paper). Future studies should include flow routing and basin water transfer; 2) Limitations on water withdrawal due to ecosystem needs. Large amounts of water are needed to satisfy environmental flows, thus greatly limiting water available for human use; 3) The impact of both climate change and land use change and urbanization on water quality and how reduced water quality can impact potable water availability.

Many federal agencies have been motivated to develop frameworks to deal with multiple stresses on future water issues. For example, the U.S. Forest Service listed climate change and water shortages as the most challenging issues among others facing the agency (http://www.fs.fed.us/kidsclimatechange/). Resources are being diverted to combat climate change and associated impacts on water through adopting mitigation and adaptation measures. In response to climate change, the U.S. EPA (2008) has released a

"*National Water Program Climate Change Strategy*" for public comment. This document has recognized the increasing threats of climate change on water resources and watersheds and developed climate change-related goals in three key topic areas of mitigation, adaptation, and research. Similarly, on May 27, 2008, the U.S. Climate Change Science Program (CCSP) released "Synthesis and Assessment Product 4.3 (SAP 4.3): The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States". The CCSP integrates the federal research efforts of 13 agencies on climate and global change. This report finds that climate change has affected U.S. water resources by increasing precipitation and streamflow, except in the West and the Southwest, where drought severity has increased significantly over the past 50 years.

The Intergovernmental Panel on Climate Change (IPCC) warns that freshwater resources are vulnerable and are to be strongly impacted by climate with a wide range of consequences on human societies and ecosystems. Research gaps exist in understanding and modeling the impacts of climate change at the scales relevant to decision making (IPCC, 2008). The model developed by this study can be used as a framework to examine future changes in water stress as induced by humans and nature. The modeling tool should be useful in facilitating integrated assessment of adaptation and mitigation strategies across multiple water sectors and agencies.

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