5 Change in the Southern U.S. Water Demand and Supply over the Next Forty Years

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5.1 INTRODUCTION

Water shortages are often considered a problem in the western United States, where water supply is limited compared to the eastern half of the country. However, periodic water shortages are also common in the southeastern United States due to high water demand and periodic drought. Southeastern U.S. municipalities spend billions of dollars to develop water storage capacity as a buffer against periodic drought. Buffers against water shortage include the development of water reservoirs and well excavation to mine ancient aquifers. It is important to have good estimates of future water supply and demand to prevent wasting money by creating more reservoir capacity than is needed by a community. Conversely, a lack of water reserve capacity can lead to the need for water restrictions.

Many factors impact the amount of water that is available and the amount of water that is required by a community. Precipitation is the major determinant of water availability over the long term. In addition to precipitation, air temperature and land cover also impact water availability by modifying how much precipitation is evaporated and transpired back into the atmosphere. Finally, ancient aquifers provide a significant proportion of needed water in some parts of the southern United States such as Texas and Arkansas. The water recharge rates for deep aquifers are very low (i.e., hundred of years), so water is essentially mined from these areas. There are also several factors that control water demand. In addition to residential water use, a great deal of water is also required by industry, irrigated farming, and the energy production sectors. In total, domestic and commercial sectors account for only 5% of the surface water use and 10% of the groundwater use. The other 95% and 90% of the surface and groundwater are used by other sectors of the economy. Thermoelectric power generation uses 50% of the surface water, and crop irrigation and livestock use 67% of the groundwater. Not all of the water that is used by each sector is lost to the atmosphere; much is quickly returned to the environment to be used again and again. The proportion of returned water varies from 98% from the thermoelectric sector to a 39% return rate from the irrigation and livestock sectors.

Communities need to accurately assess future water supply and demand if water limitations are to be minimized. However, estimates of average annual water supply and demand will be of limited use in water planning. Water shortages generally only occur during extreme event years such as when water supply may be limited by drought or when water demand is high due to drought and high air temperature. Therefore, this paper examines the sensitivity of the individual factors that influence regional water supply and demand across a range of environmental variability. Some factors such as population are relatively stable from one year to the next, while other variables such as climate can be markedly different among years. Groundwater withdrawal may be relatively stable until the supply is depleted. We will determine how much each variable is likely to influence annual water supply stress and the extent to which water supply stress may vary between 1990 and 2045.

5.2 METHODS

Water supply and demand are the two components required to assess regional water stress. We will first define the variables needed to calculate each water supply stress component and then examine how the variables change from year to year.

5.2.1 Calculations for Estimating Water Supply

We define water availability as the total potential water supply available for withdrawal for each eight-digit hydrologic unit code (HUC) watershed, expressed in the following formula (equation 5.1):

$$WS = P - ET + GS + \Sigma RF_i \tag{5.1}$$

where WS = water supply in millions of gallons for each watershed per year; P = precipitation for each watershed in cm per year; ET= watershed evapotranspiration for each watershed in cm per year, calculated by an empirical formula as a function of potential evapotranspiration, precipitation, and land cover types; and GS = historic groundwater use in millions of gallons for each watershed per year. Detailed methods are found in Sun et al. (2005).

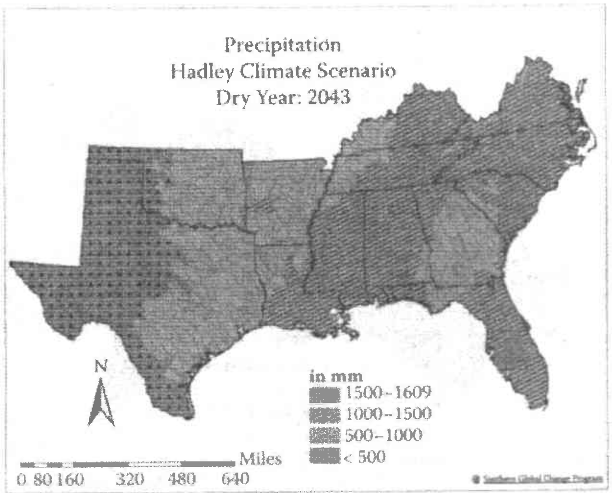
Most of the water removed for human use is returned to the environment as return flow (RF). We used RF estimates from each of seven water use sectors (WU_i) including domestic, commercial, irrigation, thermoelectric, industrial mining, and livestock sectors, which were reported by the USGS (United States Geological Survey 1994). The RF was calculated as the historical return flow rate (RFR), expressed as a fraction of the amount of removed water that was returned to the ecosystem, multiplied by the total water use (WU) for each sector, expressed in millions of gallons per year for each watershed.

5.2.2 Groundwater Supply Data

The USGS has published estimates of national water use since 1950 (Solley et al. 1998). The groundwater term (GS) is the 1990 estimate of groundwater use in millions of gallons of water per year for each eight-digit hydrologic unit code (HUC) watershed. Groundwater is defined as the saturated zone below the subsurface (Solley et al. 1993). The 1990 groundwater supply estimate was incorporated into the 1990 baseline year, 2020 wet year, and 2024 dry year water supply stress scenarios. The groundwater term was dropped for the 2043 dry year and 2045 wet year scenarios to examine the implications of a lack of groundwater availability on water supply stress.

5.2.3 Historic and Projected Climate Data

The U.K. Hadley Climate Research Center HadCM2Sul climate change scenario was used to project climate between 1990 and 2045. The southern United States is expected to become generally warmer and wetter under the HadCM2Sul scenario. We compared the impact of a future hot and dry year (Figures 5.1a and 5.1b) and a



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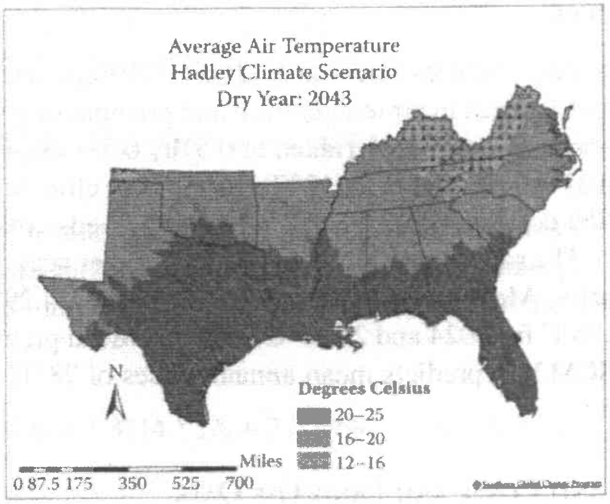
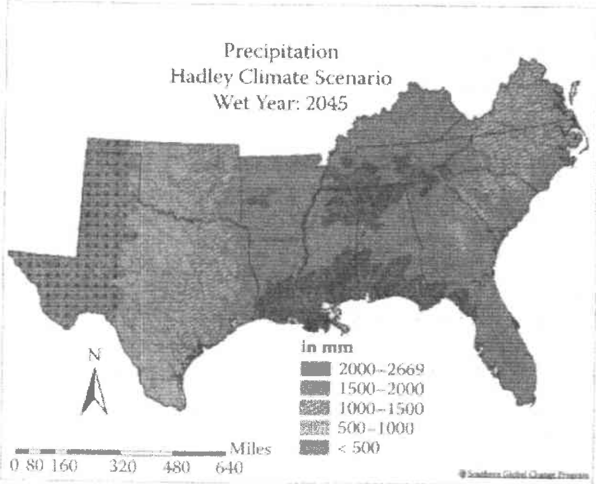


5.1b

FIGURE 5.1 Predicted hot and dry year (e.g., 2043) precipitation (a) and air temperature (b) distribution, and predicted cool and wet year (e.g., 2045) precipitation (c) and air temperature (d) distribution.



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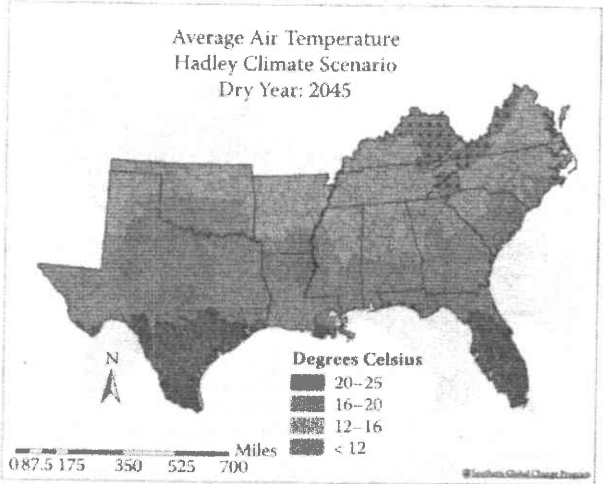


5.1d

FIGURE 5.1 (Continued)

future cool and wet year (Figures 5.1c and 5.1d) with average (circa 1990) historic climate to assess how changes in air temperature and precipitation will impact water supply stress. The climate data were gridded at 0.5° by 0.5° (about 50 km × 75 km) across the continental U.S. (Kittel et al. 1997). Next, 1990 climate data were subset and scaled to the 666 corresponding 8-digit HUC watersheds covering Virginia to Texas (USGS 1994). The same process was repeated for other years used in the water supply stress scenarios. Mean air temperature for 1990 was 24.29°C, while HadCM2Sul predicts 24.36°C for 2024 and 22.69°C for 2045. Mean precipitation for 1990 was 96.45 cm; HadCM2Sul predicts mean annual values of 78.07 cm for 2024 and 116.68 cm for 2045.

5.2.4 Historic Land Cover and Land Use Data

Land cover data were used to drive the water yield model for all seven water use sectors and each of the 666 8-digit HUC watersheds modeled in this study. The

1992 Multi-Resolution Land Characterization (MRLC) land cover/land use dataset (http://www.mrlc.gov) was used to calculate the percentage of each vegetation type within each watershed. Land cover was aggregated into five classes including evergreen forest, deciduous forest, crops, urban areas, and water. In this analysis, land use was held constant throughout the assessment period.

5.2.5 Historic and Projected Population Data

Approximately 100 million people live in the 13 southern states (U.S. Census 2002). Population projections at the census block level are available to 2050 (NPA Data Services 1999). We aggregated predicted census block–level population data to the watershed level for each year between 2000 and 2045. Between 1990 and 2045, the population of the 13 southern states was predicted to increase by 94% (NPA Data Services 1999). No new areas of growth within the region were projected, but current urban centers are expected to expand. Rural areas are generally expected to become more densely populated. However, population growth between 1990 and 2045 will not be uniform (Figure 5.2a); percentage change in population between 1990 and 2045 varied from –21% to +602% across the region (Figure 5.2b).

5.2.6 Calculations for Estimating Water Demand

Water demand is as important as water supply in determining if a community is likely to experience recurrent water shortages. Water demand (WD) represents the sum of all water use (WU) by each of the seven water use sectors within a watershed (equation 5.2):

$$WD = \Sigma WU_i \quad i = 1 - 7 \qquad (5.2)$$

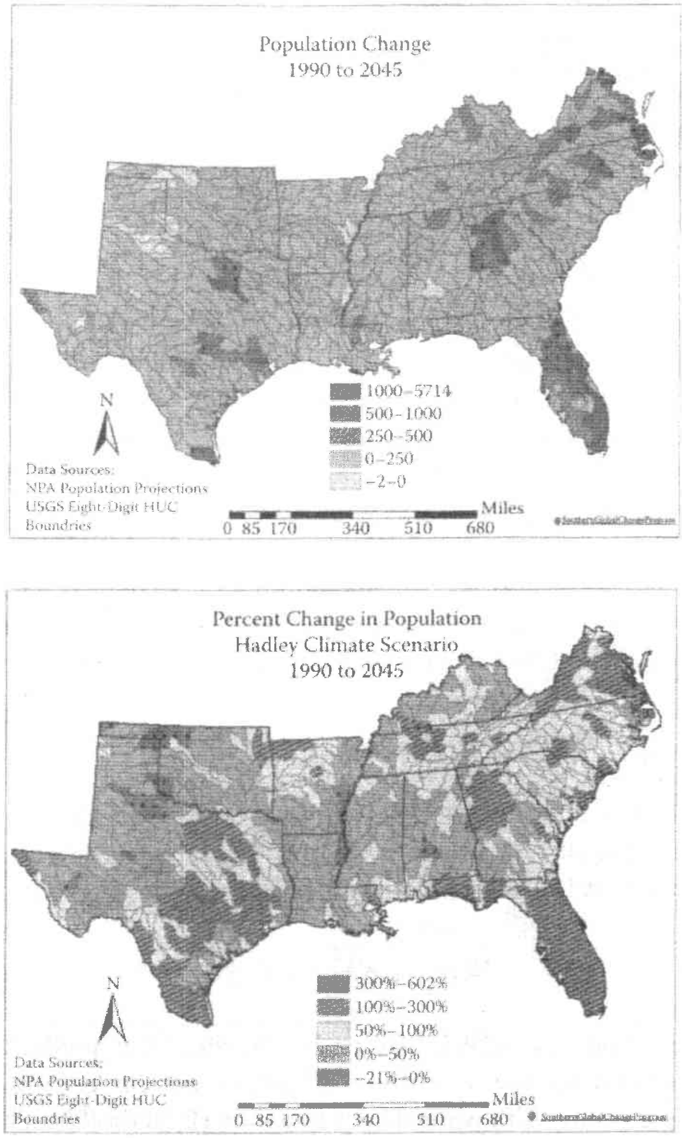
Annual domestic water use (DWU) for each watershed was predicted by correlating USGS historical water use (in millions of gallons per day per watershed) for the domestic water use sector with watershed population (P, in thousand persons) for the years 1990 and 1995 (equation 5.3):

$$DWU = 0.008706 * P + 1.34597 \qquad R^2 = 0.51, n = 666 \qquad (5.3)$$

Similarly, irrigation water use (IWU) for each watershed was derived by correlating USGS historical irrigation water use (in millions of gallons per day per watershed) with the irrigation area (IA, in thousands of acres) for the years 1990 and 1995 (equation 5.4):

$$IWU = 1.3714 * IA + 2.06969 \qquad R^2 = 0.67, n = 666 \qquad (5.4)$$

Currently, we do not have water use models for the other five sectors (i.e., commercial, industrial, livestock, mining, and thermoelectric), therefore historic water use data were utilized for future periods.



5.2a

5.2b

FIGURE 5.2 The spatial and temporal change in southern U.S. population between 1990 and 2045 expressed as absolute change (a) and percentage change (b).

5.2.7 Calculations for Estimating the Water Supply Stress Index (WASSI)

We have defined a water supply stress index (WASSI) by dividing water supply by water demand (equation 5.5). Comparing the WASSI between two points in time results in a WASSI ratio (WASSIR, equation 5.6). The WASSI was used to quantitatively assess the relative magnitude in water supply and demand at the 8-digit HUC watershed scale. The WASSIR was used to assess the relative change in the WASSI between the baseline scenario (SI_l) and one of the other scenarios (SI_x) described later. Positive WASSIR values indicate increased water stress and negatives values indicate reduced water stress compared to historical conditions (scenario 1):

$$WASSI_x = \frac{WD_x}{WS_x} \tag{5.5}$$

and

$$WASSIR_x = \frac{WASSI_x - WSS_1}{WASSI_1} \tag{5.6}$$

where x represents one of six simulation scenarios described below.

5.2.8 Water Supply Stress Scenarios

Six scenarios were developed, each examining the impacts of changing population, climate, and ground water supply on annual WASSI values. Changes in the water supply portion of the WASSI term were addressed in three ways. First, we chose two dry years (2024 and 2043) and two wet years (2020 and 2025) to compare to the historic climate base year of 1990. Second, ground water is a finite resource and given the current rate of usage, it is possible that ground water may be completely depleted in some areas during the next 40 years. We tested the impact of the loss of ground water supply on water supply stress by examining wet and dry years with and without ground water inputs into the WASSI model. Finally, population impacts on water supply stress were examined by comparing wet and dry years in the 2020s and 2040s with the baseline water supply stress year (i.e., 1990).

5.2.8.1 Scenario 1: Small Population Increase—Wet Year (2020)

This scenario used 2020 population projections that predicts above average precipitation for the region compared to 1990 values. Groundwater withdrawal was held constant at 1990 levels.

5.2.8.2 Scenario 2: Small Population Increase—Dry Year (2024)

This scenario used 2024 population projections. 2024 is predicted to have below average precipitation compared to 1990 levels, thus decreasing water supply. Groundwater withdrawal was held constant at 1990 levels.

5.2.8.3 Scenario 3: Large Population Increase—Wet Year (2045)

This scenario used 2045 population projections, and it is predicted to have above average precipitation compared to 1990 levels. Groundwater withdrawal was held constant at 1990 levels.

5.2.8.4 Scenario 4: Large Population Increase—Dry Year (2043)

This scenario used 2043 population projections, that is predicted to have below average precipitation compared to 1990 levels. Groundwater withdrawal was held constant at 1990 levels.

5.2.8.5 Scenario 5: Large Population Increase—Wet Year (2045), No Groundwater Supply (GS)

This scenario used 2045 population projections that is predicted to have above average precipitation compared to 1990 levels. However, groundwater supplies may be exhausted in some areas by 2045. Therefore, we removed groundwater for the entire region as a water supply source to the WASSI model in this scenario.

5.2.8.6 Scenario 6: Large Population Increase—Dry Year (2043), No Groundwater Supply (GS)

This scenario used 2043 population projections that is predicted to have below average precipitation compared to 1990 levels. In addition to the increased population and below average year precipitation, the groundwater supply was removed from the WASSI model across the region in this scenario.

5.3 RESULTS AND DISCUSSION

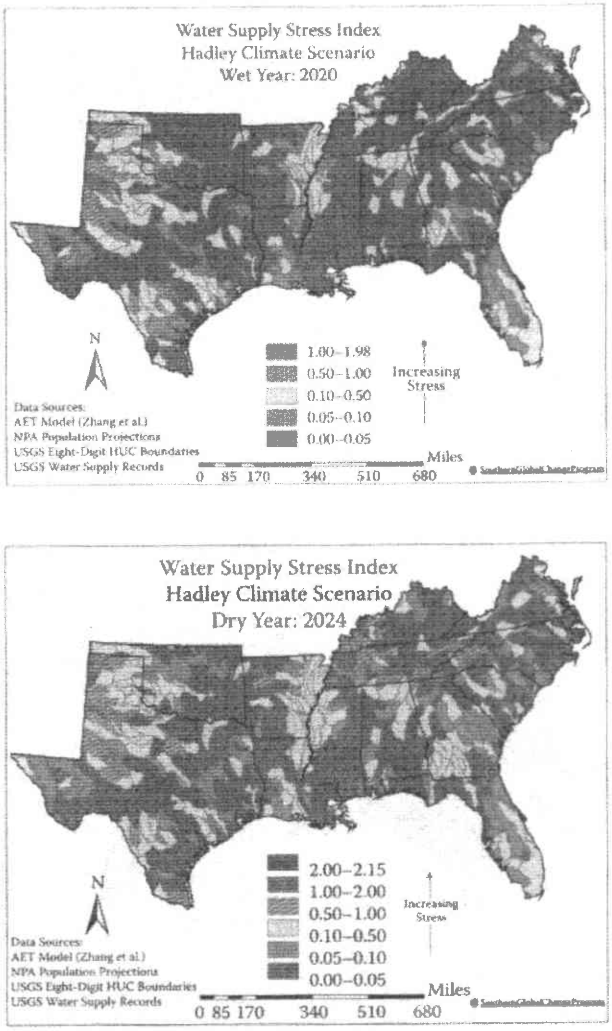
The results section is divided into three parts: (1) climate controls on water supply stress, (2) population and other water use sector controls on water supply stress, and (3) ground water supply controls on water supply stress.

5.3.1 Climate Controls on the WASSI

Historically, annual precipitation and air temperature vary widely 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. Annual precipitation and air temperature are the most important determinants of water loss by evapotranspiration and thus water yield across the southern United States (Lu et al. 2003). Therefore, the Appalachians and the Gulf coast had the highest water availability, while the lowest was found in semiarid western Texas.

Irrigation and thermoelectric sectors were the two largest water users, followed by domestic livestock and industrial users. Consequently, the western Texas region, which had a lot of irrigated farmland and limited water supplies, had the highest WASSI for both wet and dry years (Figures 5.3a–d). Other areas with WASSI values indicating stress included southern Florida, southern Georgia, and Mississippi valley areas with a high percentage of irrigated land (relative to the total land area). Several isolated watersheds in high-precipitation regions east of the Mississippi River also showed high water stress, primarily due to thermoelectric water use.

Compared to the baseline conditions of 1990, the WASSI in 2020 (Figure 5.3a) and 2045 (not shown) were projected to decrease due to a moderate increase in air temperature and a large increase in precipitation. The WASSI in 2024 (Figure 5.3b) was projected to increase due to a moderate temperature increase and moderate decrease in precipitation compared to 1990 levels. As a result, the average regional WASSIR value (compared to 1990) decreased by 5% during the wet year of 2020 (Figure 5.3c), but increased by 22% for the dry year of 2024 (Figure 5.3d) and 66%



5.3a

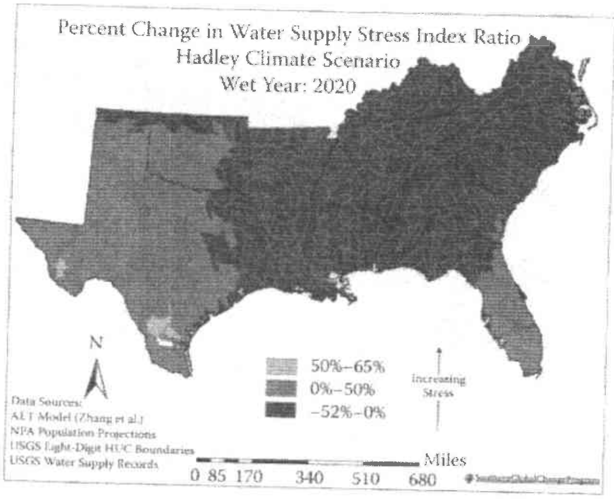
5.3b

FIGURE 5.3 Climate change impacts on the southeastern U.S. water supply stress (WASSI) during the wet year of 2020 (a) and the dry year of 2024 (b). Change in the water supply stress ratio (WASSIR) between the 1990 baseline WASSI and the wet year WASSI of 2020 (c) and the dry year WASSI of 2024 (d).

for the dry year of 2043 (not shown). The WASSIR again decreased for the dry year of 2045 by 4% (not shown).

5.3.2 Population and Other Water Use Sector Controls on the WASSI

Water demand by the domestic water use sector is directly related to population, as demonstrated in Equation 5.3. Population centers that are projected to expand dramatically over the next 40 years (e.g., Atlanta, Georgia; Dallas, Texas; Raleigh-Durham, North Carolina; and northern Virginia) will see up to 200% increases in domestic water use. Therefore, population growth may be responsible for increasing the WASSI by more than 70% in watersheds containing relatively large increases in population, but population change will have little impact (<5%) on the regional-scale WASSI.



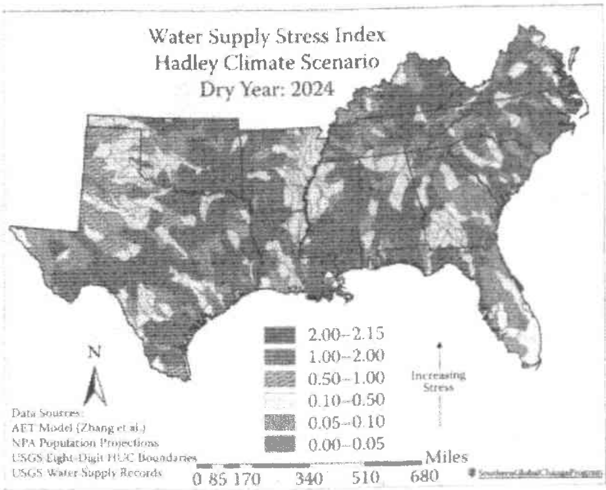
5.3c

5.3d

FIGURE 5.3 (Continued)

The mean regional WASSI increased from 0.11 (Figure 5.4a) to 0.12 (Figure 5.4b), despite a 30% increase in southeastern U.S. population between 2024 and 2043. Population changes had little impact on the WASSI when compared to that of the interannual variation in climate and potential loss of groundwater reserves. A doubling of local populations around metropolitan areas will have a limited impact on interannual WASSI variability. Even in heavily populated areas, residential and commercial water use represent small segments of total water demand, but cities do affect water quality. As the population increases, costs for water treatment and acquisition increase; water conservation may be important for reasons other than water supply.

Other sectors, such as hydroelectric power generation, use much more water than other sectors but also recycle approximately 98% of the water that is used. In contrast, the irrigated farming sector uses a large share of the total water supply while returning only approximately 68% of the water back to the land; the rest is lost to evaporation.



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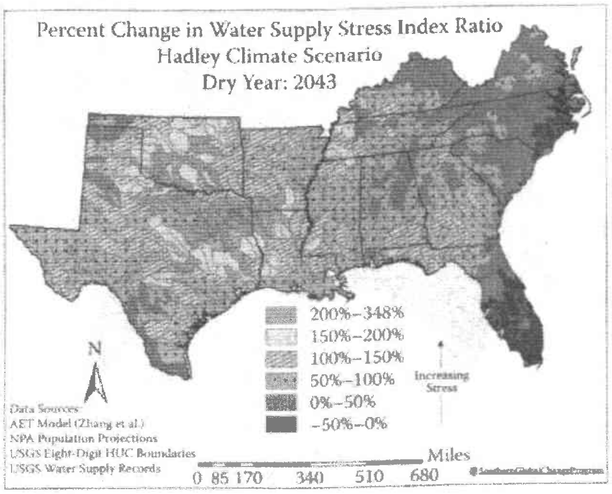
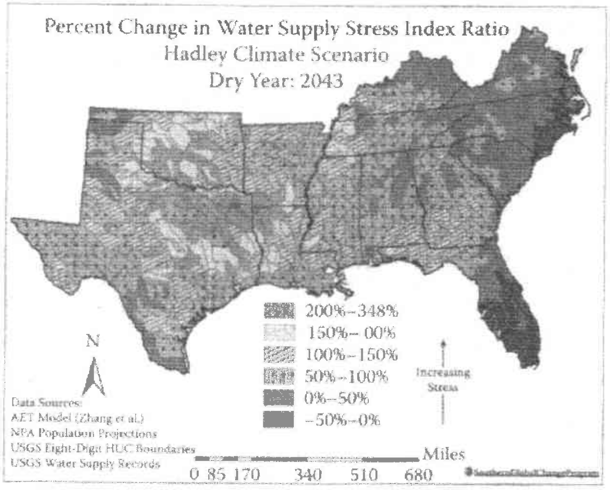


5.4b

FIGURE 5.4 Population change impacts on the southeastern U.S. water supply stress (WASSI) during a dry year in 2024 (a) and a dry year in 2043 (b). Change in the water supply stress ratio (WASSIR) between 1990 and the two dry years of 2043 (c) and 2024 (d).

5.3.3 Ground Water Supply Controls on the WASSI

The loss of the groundwater resource can have severe implications for the WASSI in some areas where groundwater represents a major source of the water supply. By the 2040s, it is likely that areas with limited aquifer reserves and heavy groundwater use will begin to run out of groundwater. In our study, we expected loss of groundwater to have a severe impact on the WASSI during the dry year of 2043 (Figure 5.5a). It was somewhat surprising that even during the projected wet year of 2045, severe water stress would occur over much of the region without groundwater (Figure 5.5b). The water supply stress index ratio (WASSIR) increased by 232% between the baseline year of 1990 and the dry, no groundwater year of 2043 (Figure 5.5c). Even for the wet year/no groundwater scenario of 2045, the WASSIR difference between 1990 and the dry years without groundwater (i.e., 2024 and 2043) was 119% (Figure 5.5d).



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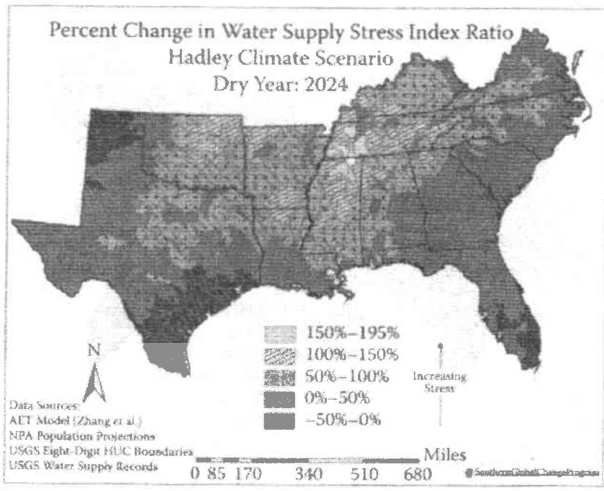


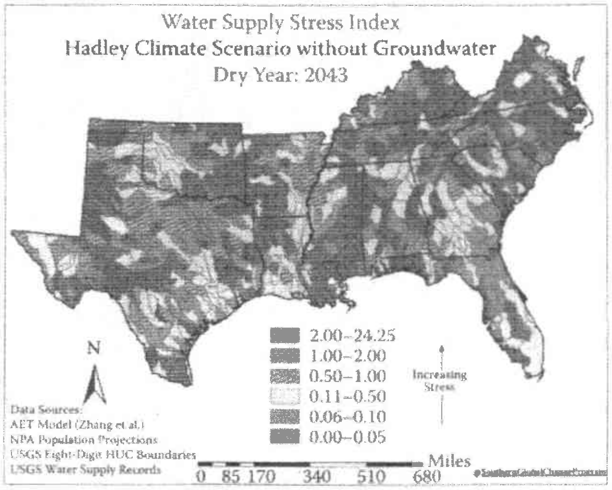
5.4d

FIGURE 5.4 (Continued)

Land use planners should carefully review the implication of groundwater loss on local economies and consider converting land area from higher to lower water-consuming practices (e.g., reduce irrigated acreage) or the use of water transport systems to replace exhausted aquifers. Even the most optimistic estimates of climate change and increased precipitation will not likely alleviate future water stress, should aquifers run dry.

5.4 SUMMARY

This paper explored the likely impacts of climate, population, and groundwater supply on interannual water supply stress across the southeastern United States during the next 40 years. We found that predicted climate variability will have the largest impact on the water supply stress. However, the current WASSI model does not carry water reserves or deficits from one year to the next. There is no drawdown of water reservoir capacity as would occur during a prolonged drought. Similarly, there is no



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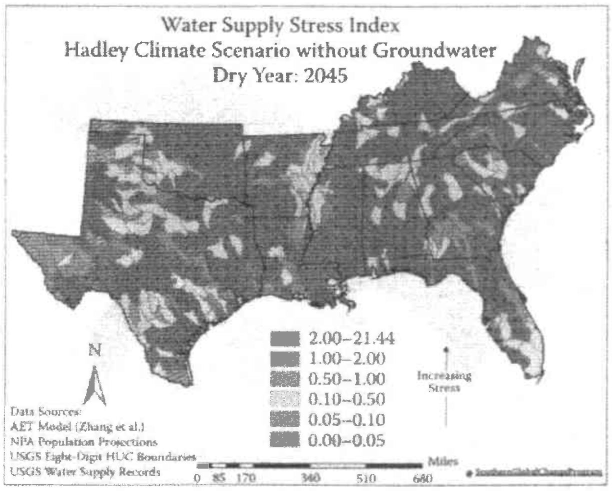
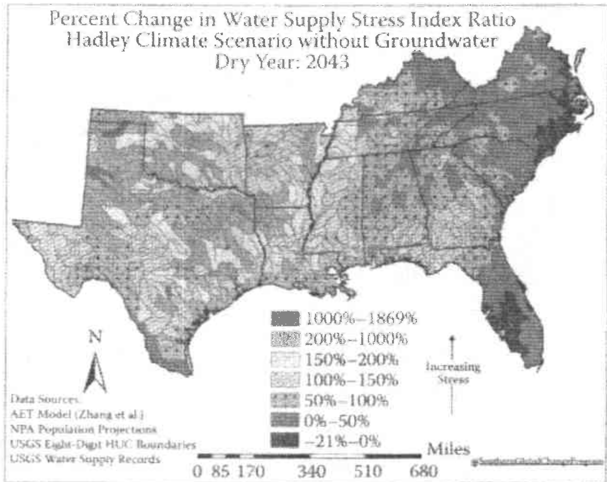


5.5b

FIGURE 5.5 Climate change impacts on the southeastern U.S. water supply stress (WASSI) during the dry year 2043 if no groundwater were available (a) and the wet year of 2045 with no available groundwater (b). Change in the water supply stress ratio (WASSIR) between 1990 and the dry year of 2043 if no groundwater were available (c) and the wet year of 2045 with no available groundwater (d).

reserve water capacity to compensate for water shortfalls during a drought. Therefore, the current WASSI model could overestimate the impact of short-term droughts because water deficits could be offset by water reservoirs.

Watersheds receiving limited precipitation and with a heavy dependence on groundwater will be the most susceptible to chronic and potentially permanent water shortages. Water use managers should expect even more stress in large population centers. 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 climate change–induced precipitation patterns remain uncertain, especially in the eastern United States, and thus realistically predicting future water stress remains a challenge.



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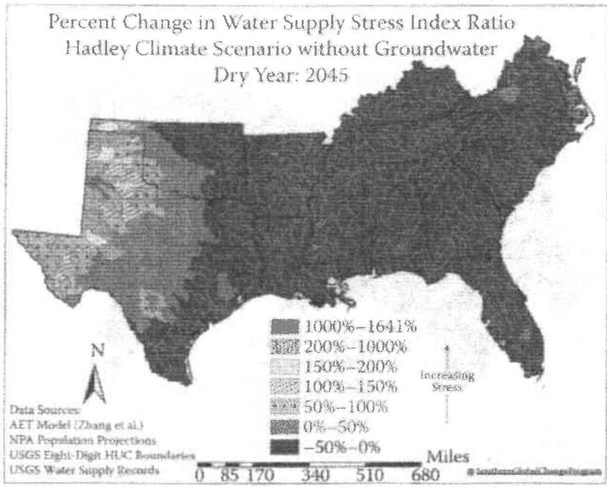

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FIGURE 5.5 (Continued)

ACKNOWLEDGMENTS

Funding for this work was provided by the U.S. Department of Agriculture Forest Service Southern Global Change Program in Raleigh, North Carolina. The authors thank Corey Bunch for programming support.

REFERENCES

Brown, R. A., N. J. Rosenberg, and R. C. Izarraulde. 1999. *Responses of U.S. regional water resources to CO_2-fertilization and Hadley center climate model projections of greenhouse-forced climate change: A continental scale simulation using the HUMUS model.* Richland, WA: Pacific Northwest National Laboratory.

Kittel, T. G. F., J. A. Royle, C. Daly, N. A. Rosenbloom, W. P. Gibson, H. H. Fisher, D. S. Schimel, L. M. Berliner, and VEMAP2 Participants. 1997. A gridded historical (1895–1993) bioclimate dataset for the conterminous United States. In *Proceedings of the 10th Conference on Applied Climatology*. Boston, MA: American Meteorological Society, 219–222.

Lu, J., G. Sun, D. M. Amatya, and S. G. McNulty. 2003. Modeling actual evapotranspiration from forested watersheds across the southeastern United States. *Journal of American Water Resources Association* 39(4):886–896.

NPA Data Services, Inc. 1999. Economic databases—mid-range growth projections 1967–2050. Regional Economic Projections Series, Arlington, VA: NPA Data Services.

Solley, W. B., R. R. Pierce, and H. A. Perlman. 1993. *Estimated use of water in the United States in 1990.* USGS Circular 1081. Reston, VA: U.S. Geological Survey.

Solley, W. B., R. R. Pierce, and H. A. Perlman. 1998. *Estimated use of water in the United States in 1995.* USGS Water Resources of the United States. USGS Circular 1200. Reston, VA: U.S. Geological Survey.

Sun, G., S. G. McNulty, J. Lu, D. M. Amatya, Y. Liang, and R. K. Kolka. 2005. Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States. *Journal of Hydrology*, 308:258–268.

U.S. Census Bureau. 2002. Perennial Census Data. Retrieved April, 15, 2002, from http://www.census.gov.

U.S. Geological Survey, Water Resources Division. 1994. *Hydrologic unit maps of the coterminous United States: 1:250,000 scale, 8-digit hydrologic unit codes and polygons.* Reston, VA: U.S. Geological Survey.