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EVALUATION OF THE SUSTAINABILITY OF WATER WITHDRAWALS IN THE UNITED STATES, 1995 TO 2025[1]

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ABSTRACT: To evaluate the long term sustainability of water withdrawals in the United States, a county level analysis of the availability of renewable water resources was conducted, and the magnitudes of human withdrawals from surface water and ground water sources and the stored water requirements during the warmest months of the year were evaluated. Estimates of growth in population and electricity generation were then used to estimate the change in withdrawals assuming that the rates of water use either remain at their current levels (the business as usual scenario) or that they exhibit improvements in efficiency at the same rate as observed over 1975 to 1995 (the improved efficiency scenario). The estimates show several areas, notably the Southwest and major metropolitan areas throughout the United States, as being likely to have significant new storage requirements with the business-as-usual scenario, under the condition of average water availability. These new requirements could be substantially eliminated under the improved efficiency scenario, thus indicating the importance of water use efficiency in meeting future requirements. The national assessment identified regions of potential water sustainability concern; these regions can be the subject of more targeted data collection and analyses in the future.

(KEY TERMS: water use; precipitation; thermoelectric generation; water storage; future water demand; water use efficiency.)

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INTRODUCTION

The availability of sufficient water of adequate quality for human use and for supporting a healthy environment is essential for the long term stability of a region. Over time, the growth of any economy or region is predicated on sustainable water resources, defined to include both quantity and quality for humans as well as aquatic ecosystems. The goal of this study was to use available data on water withdrawal for different uses, to make reasonable estimates of the expected changes in withdrawal until 2025, and to assess the water sources that can meet these withdrawal requirements. For the purpose of this discussion, sustainability is defined as the ability to meet future water demands, given current status and trends of withdrawals, using existing water sources. Economic effects, such as the impact of shifts in demands due to a changed price structure, are not considered. This study was motivated by a general awareness that in coming decades, demand increases due to population growth will lead to water sustainability concerns in many parts of the country. A recent report by the Congressional General Accounting Office, based on a survey of water managers, confirms that 36 states anticipate water shortages in the next 10 years, even under normal water conditions, and 46 states expect water shortages under drought conditions (GAO, 2003). The last comprehensive national assessment of water availability and use was conducted by the federal government in 1978 (Water Resources Council, 1978).

The task of evaluating future water sustainability is complicated by increasing demand and possible limits on supply. Human needs are growing with increasing population, both for direct consumption and also indirectly for energy production and agricultural,

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commercial, and industrial activity. Although there is an absolute minimum water use that is needed for direct human consumption, the indirect uses are substantially greater, and there is room for improving the efficiency of such uses. On the supply side, with the better understanding of anthropogenic influences on ecosystems that has come about in recent decades, there is greater pressure to minimize the impacts to natural ecosystems as additional withdrawals of water for supporting growth in demand are considered.

WATER AVAILABILITY, WITHDRAWAL, AND STORAGE IN THE UNITED STATES IN 1995

As a first step toward evaluating the longer term sustainability of water withdrawals, a county level analysis of the availability of renewable water resources was conducted, and the magnitudes of human withdrawals from surface water and ground water sources and the stored water requirements during the warmest months of the year were evaluated. Water availability was assessed using data obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC, 2003), and water use was based on U.S. Geological Survey (USGS) water use surveys conducted as part of the National Water Use Information Program. These surveys were first conducted in 1950 and have been conducted every five years. In this study, the 1995 data are used for most of the analysis (Solley *et al.,* 1998), except for selected national aggregate withdrawal comparisons, for which the 2000 data have been used (Hutson *et al.,* 2004). On an aggregate basis, freshwater withdrawals for 2000 are almost identical to the 1995 withdrawals. County level data for 2000 have recently been made available, although a detailed evaluation was beyond the scope of this study.

Estimating Water Availability in the United States

In a basin, precipitation as rain or snow is the main source of renewable water. Some of the precipitation is lost to the atmosphere by evaporation or through transpiration by plants (these two processes are usually lumped together and termed “evapotranspiration”). The remainder percolates into the ground and is stored as ground water or is transported as runoff. Precipitation as snow is also stored above ground when the temperatures are below freezing. The water budget for a region is usually expressed as

$$P = R + I + ET + \text{change in storage}$$

where P is precipitation, I is infiltration, and ET is evapotranspiration. The availability of renewable water in a region may be estimated by the amount of available precipitation, defined as the difference between precipitation and potential evapotranspiration (PET) summed for all months in the year in which precipitation exceeds PET. Precipitation and PET data from NOAA, averaged from 1934 to 2002 for the 344 climate divisions covering the continental United States, were used to calculate the available precipitation, in inches per year (shown in Figure 1). Much of the western United States, except some coastal areas, has far lower water availability than the eastern United States. In the eastern United States, water availability is lower in regions with higher PET, such as South Florida. For consistency with calculations that follow, this map shows values at the county level estimated from data at the climate division level. The location of the centroid of a county was used to assign that county to a climate division.

Water Withdrawals in the United States in 1995

On a national aggregate basis, Figure 2 shows the withdrawal and consumptive use of freshwater (the fraction that evaporates during use) for each of the six major categories: agriculture, thermoelectric cooling, domestic, industrial, commercial, and mining. Agricultural and cooling water withdrawals are the dominant components of the total water withdrawal nationwide (40 percent and 39 percent, respectively). Although thermoelectric cooling use is a major fraction of the withdrawal, most of this use is not consumptive and makes for a relatively modest fraction (3 percent) of the total consumptive use. Irrigation is the most significant consumptive user of water (82 percent). Consumptive water use for domestic purposes is the second most significant use (7 percent). Note that withdrawal and consumptive use are distributed nonuniformly throughout the nation; hence, national aggregate percentages may be unrepresentative of an individual county, state, or region.

Figure 3 shows the total withdrawal of freshwater for all uses from surface water and ground water sources in 1995. The withdrawals are expressed in units of inches per year to allow for comparison across counties of differing sizes. Areas with significant total freshwater withdrawal are scattered throughout the country with some hot spots in California, Florida, Arkansas, Missouri, the Great Lakes region, eastern Washington, Idaho, Louisiana, and eastern Texas. Most areas of the United States in 1995 were within 15 percent of their means for 1934 to 2002. This is

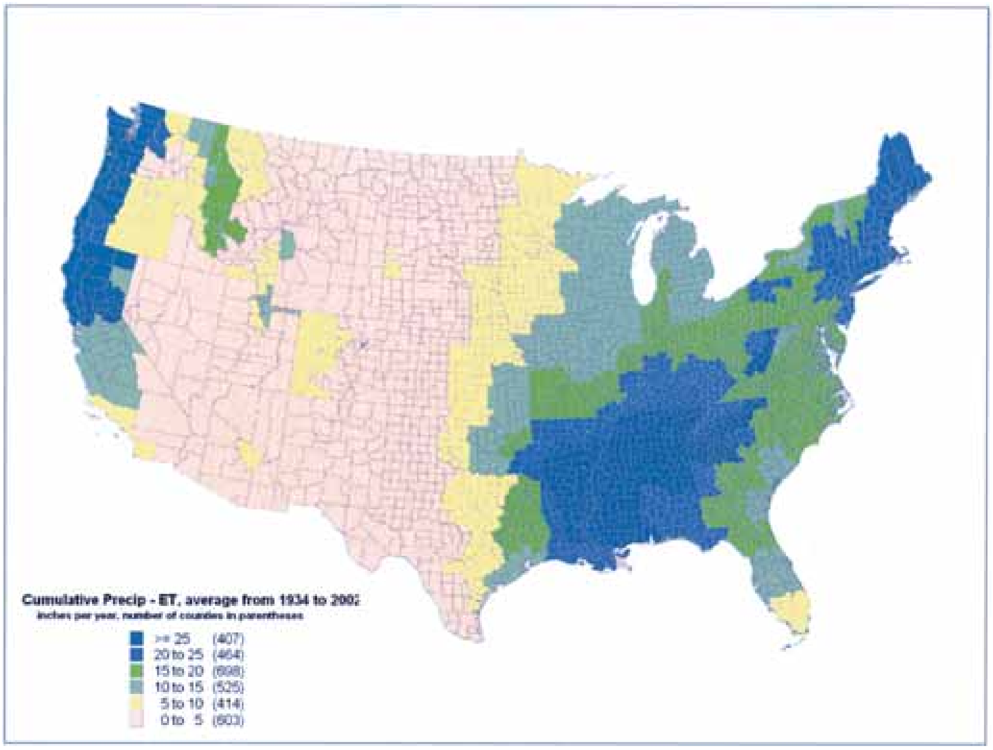

Figure 1. Available Precipitation (difference between monthly precipitation and potential evapotranspiration, sum of months with nonzero values, as defined in the text) Across the United States, Based on 1934 to 2002 Average Data at the Climate Division Level (data from CPC, 2003).

important because the water use data may have been skewed in an unusually wet or unusually dry year.

Total freshwater withdrawals are plotted as a percentage of available precipitation in Figure 4. Areas where this ratio is greater than 100, i.e., where more water is used than locally renewed through precipitation, are indicative of basins using other water sources transported by natural rivers or man made flow structures. In some cases, they may also be indicative of unsustainable ground water withdrawal. Areas where this ratio is high are concentrated in the western United States, most notably in the Southwest. The ratio of ground water withdrawal to available precipitation is shown in Figure 5. Ground water is an important resource because it can provide a supply during the driest months of the year and if the source aquifer storage is large enough can provide a buffer capacity during drought years. The available precipitation is the maximum amount of water that can percolate into ground water in a region (in reality, a substantial fraction will not enter ground water but will be transported in surface water bodies). When this ratio exceeds 100 percent, it is an indication that the ground water withdrawal exceeds local replenishment. In many cases this may be indicative of unsustainable ground water withdrawal unless interbasin transfers or recharge occurs. For the United States, it appears that this ratio exceeds 100 percent in the parts of Kansas, Nebraska, and northern Texas that overlie the High Plains (Oglalla) Aquifer, a well known overdraft area (USGS, 1999), and Arizona and southern California. It is also high in Idaho, southern Florida, and California's Central Valley. The two largest components of withdrawal, for agriculture and for thermoelectric cooling, are also of interest from the perspective of estimating future withdrawals, as discussed in the following section.

Estimating the Use of Stored Water in the United States

One of the shortcomings of the data in the USGS water use database is the limited amount of information on available storage volumes (in lakes, reservoirs, ground water, and snowpack) across the nation. The development of data in this area is one of the long term goals of the USGS (USGS, 2002). For the purpose of this analysis, a relatively simple approach to estimating withdrawal of stored freshwater on a national scale has been developed. Storage withdrawals are greatest during the warmest months of the year, which also are often the driest months in many parts of the country and are assumed to be the

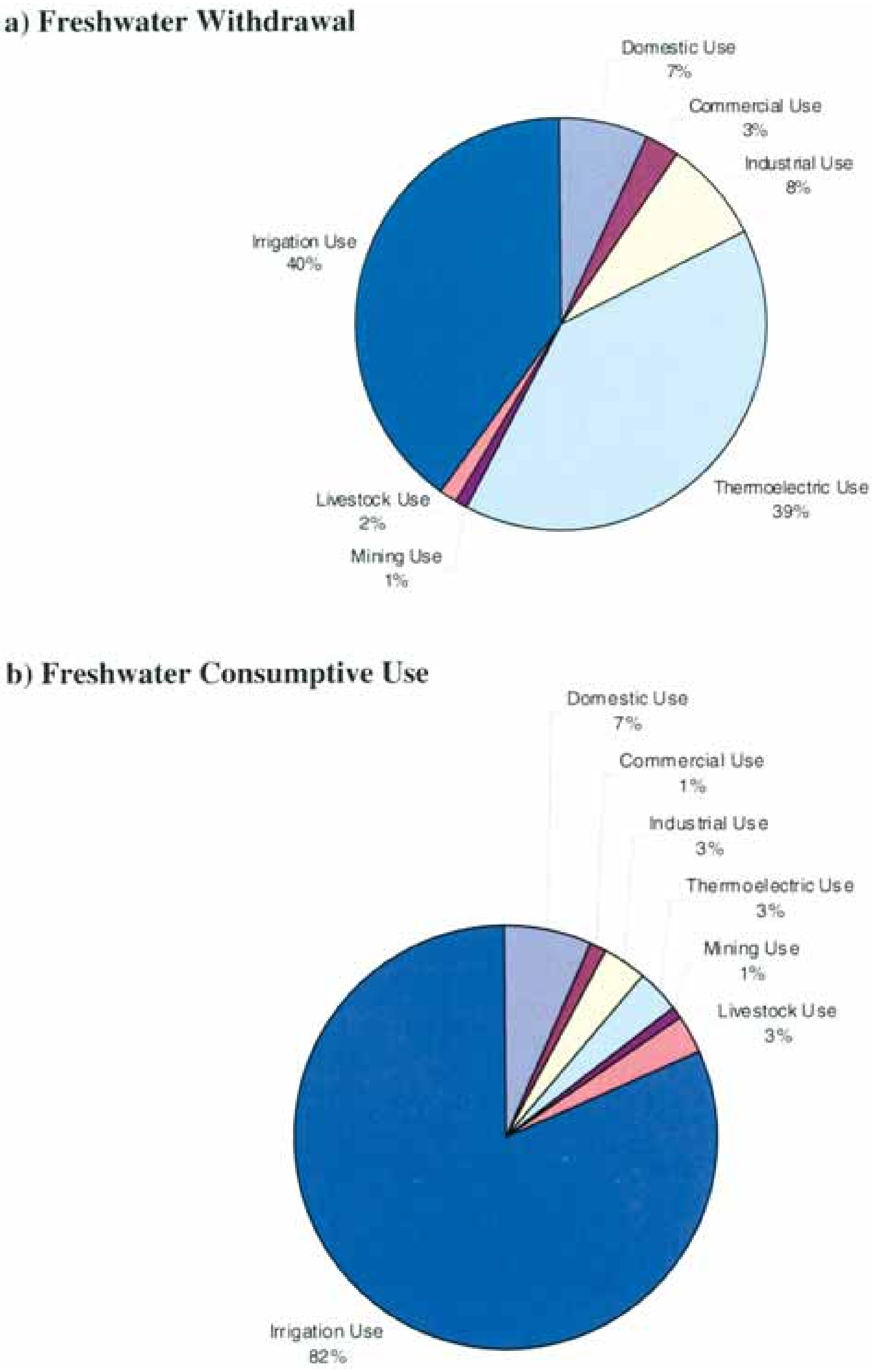

Figure 2. (a) Aggregate National Withdrawals and (b) Consumptive Use of Freshwater in 1995. The total freshwater withdrawal was 342 billion gallons per day, and the total consumptive use is about 100 billion gallons per day. Based on data from Solley *et al.* (1998) and CPC (2003).

months of July, August, and September. The difference between the available precipitation and the water withdrawal during July, August, and September is an estimate of existing stored water withdrawal infrastructure. Because monthly water use data were not available, the following assumptions were made to estimate the withdrawal for the summer months from the annual freshwater withdrawal.

- Irrigation water application during each month of the year was assigned in proportion to the difference between precipitation and PET, for months when

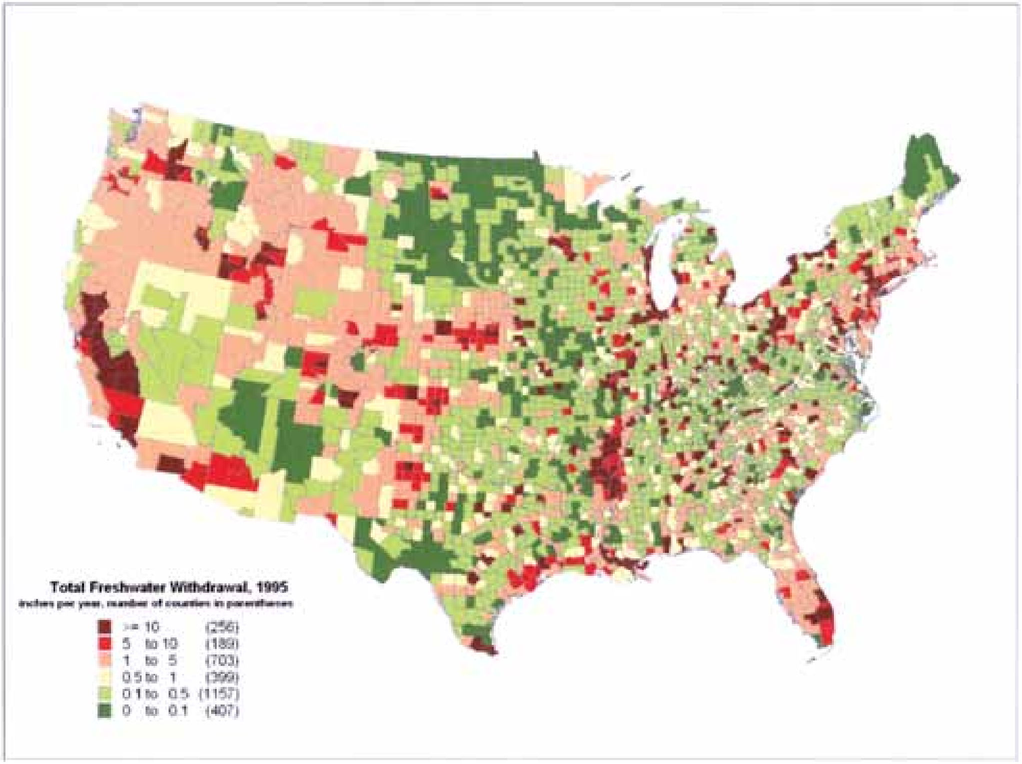

Figure 3. Total Freshwater Withdrawals From Surface Water and Ground Water Sources in 1995 for the United States, Normalized to Inches Per Year to Account for Counties of Different Area. Based on data from Solley *et al.* (1998).

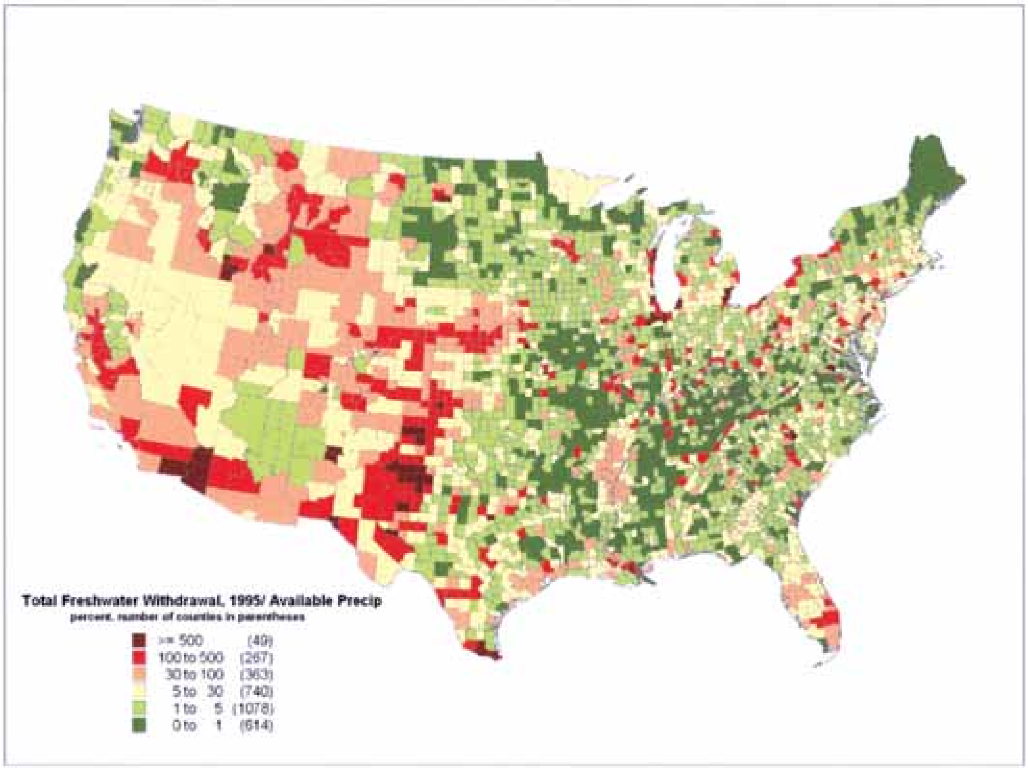

Figure 4. Total Freshwater Withdrawals in 1995 as Percent of Available Precipitation. Higher values indicate a greater level of water resources development. Values greater than 100 indicate water imports. Based on data from Solley *et al.* (1998) and CPC (2003).

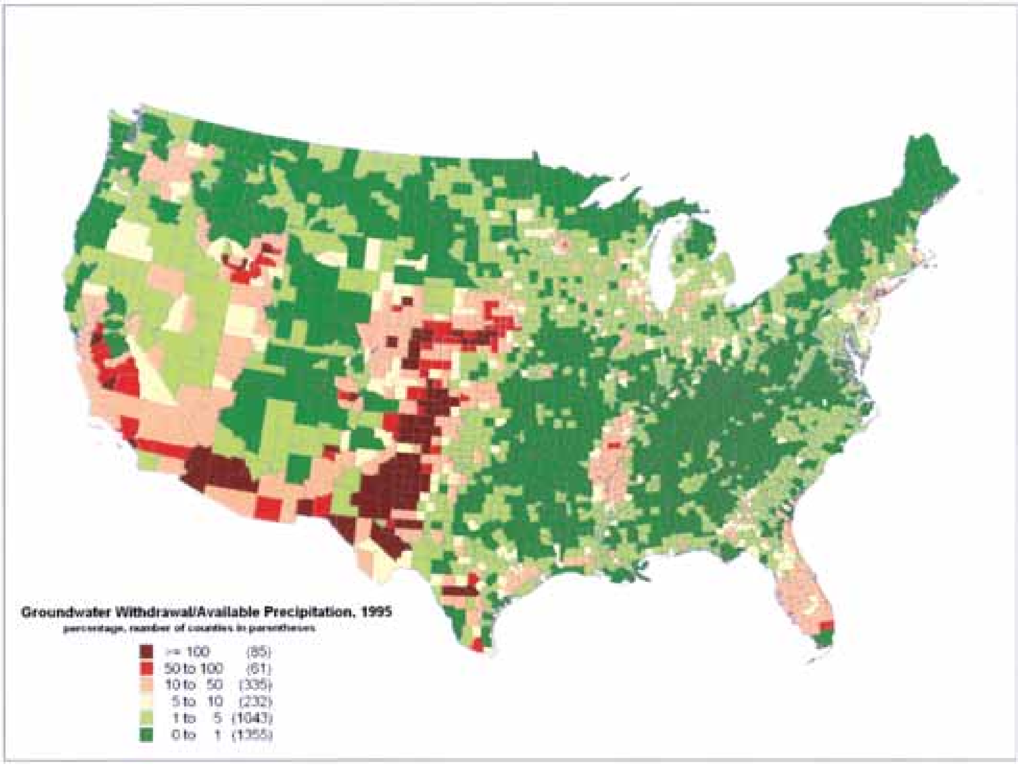

Figure 5. Ground Water (fresh) Withdrawals in 1995 as a Percent of Available Precipitation. Based on data from Solley *et al.* (1998) and CPC (2003).

PET exceeds precipitation, using essentially the same approach as is used in the field.

- Thermoelectric cooling withdrawal was assumed to be proportional to electricity generation, and 28 percent of the annual total was assumed to occur during the summer months, based on national monthly generation data from the Energy Information Administration (EIA), with additional details provided in EPRI (2003).
- For domestic use, it was assumed that half the use was based on a uniform distribution through the year, and half was based on the precipitation PET difference similar to that used for irrigation, reflecting the variability of outdoor domestic use that varies seasonally.
- Other withdrawals were assumed to be uniform during the year with 25 percent of the annual withdrawal during July, August, and September.

The availability of more temporally detailed water use data may be used to refine these assumptions in the future. The summer deficit for 1995, an index of stored water needs and defined as available precipitation minus withdrawal in July, August, and September, is plotted in Figure 6. Many regions of the country, both in the eastern and western United States, had substantial summer deficits in 1995 that were met through some combination of stored water, such as snowmelt, reservoir or lake storage, and ground water. Western regions, although drier, may have a more extensive infrastructure for supplying stored water during the summer months (e.g., the Upper and Lower Colorado Water Resource Regions have reservoir capacity more than two times the annual renewable supply; Guldin, 1989). The summer deficit map is an indirect representation of the water from stored sources supplied by the existing water infrastructure in different regions of the country.

The summer deficit for withdrawals at 1995 levels during years when the precipitation is much lower than in 1995 can also be evaluated. This is shown in Figure 7, where the summer deficit is calculated for precipitation corresponding to the lowest calculated three-year rolling average value over 1934 to 2002 for each climate division using NOAA precipitation data and PET estimates (CPC, 2003). As expected, the areas of significant summer deficit are now much larger and are more widespread in the eastern United States. Figure 7 shows that if a dry year such as that represented by lowest three-year rolling average precipitation were to occur, stored water withdrawal requirements would be larger than they were in 1995, and constraints on water use during the driest months of the year would be widespread across the

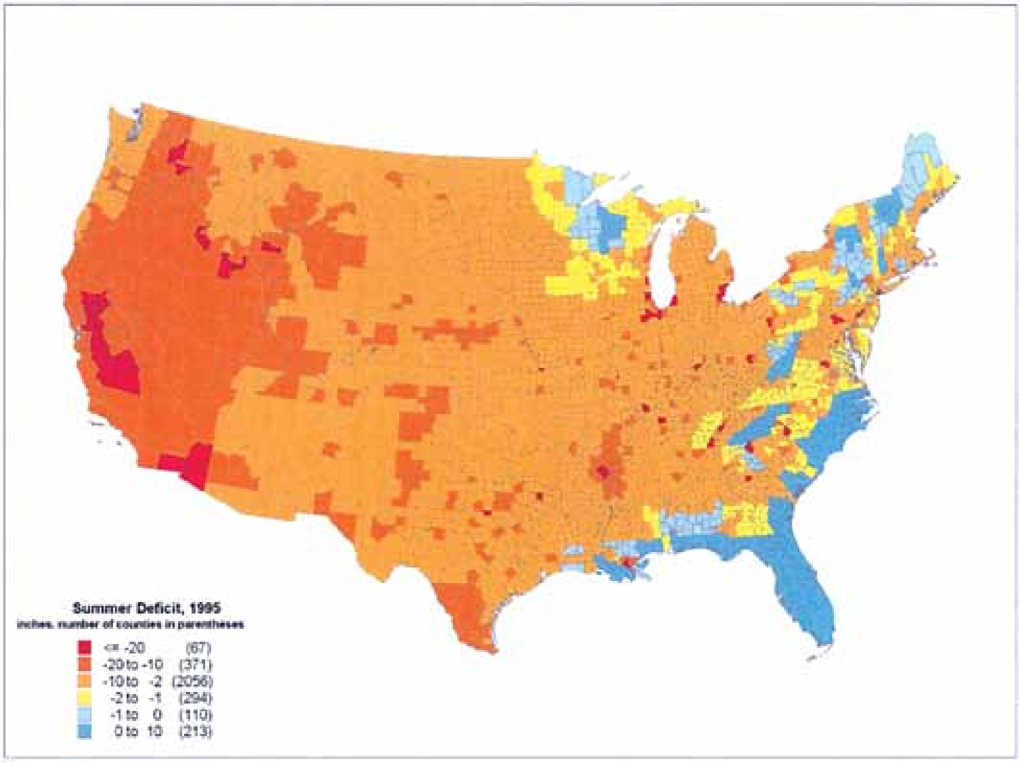

Figure 6. Summer Deficit for 1995, Defined as the Available Precipitation Minus Withdrawals in July, August, and September. Based on data from Solley *et al.* (1998) and CPC (2003).

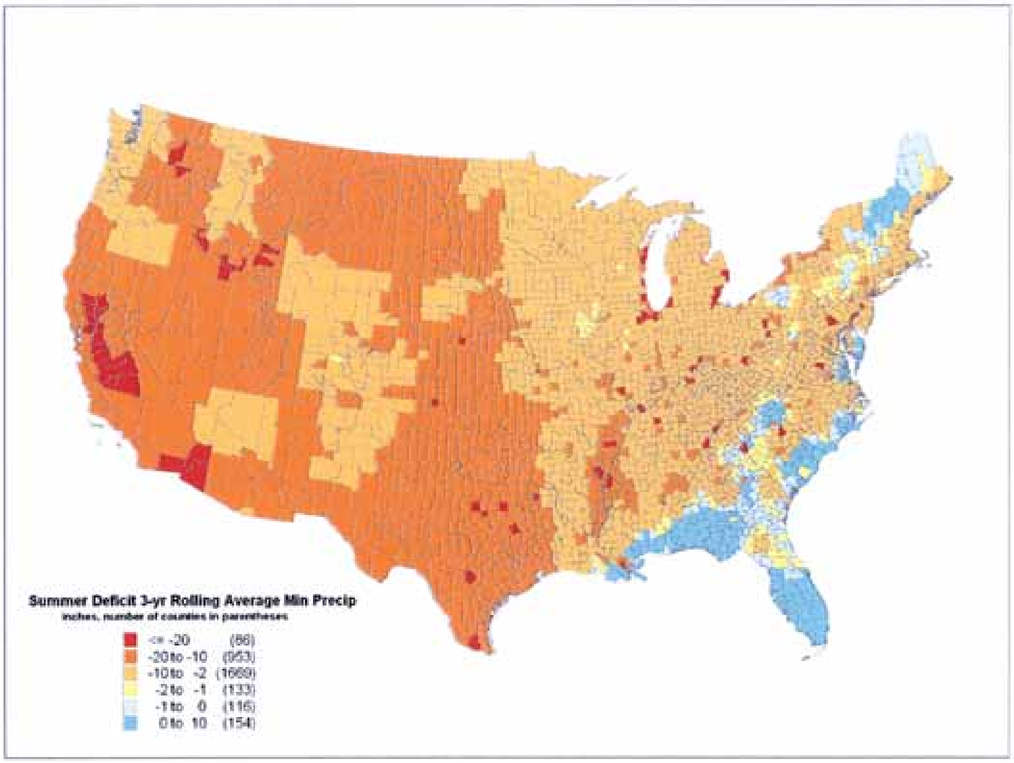

Figure 7. Summer Deficit for 1995 Withdrawals Using the Lowest Three-Year Rolling Average Precipitation Over 1934 to 2002. Calculated based on data from Solley *et al.* (1998) and CPC (2003).

United States and not limited to what are thought to be arid regions.

AN APPROACH TO ESTIMATING SUSTAINABILITY OF WATER USE IN 2025

To a certain extent, the county level picture of water use across the United States in 1995 is sufficient to identify regions where future water supply shortages may occur. However, there are two limitations to depending solely on past data to draw conclusions on future water sustainability. First, many factors that affect current total freshwater withdrawal are likely to change, especially population and power generation, and a more realistic projection of future areas of water scarcity must take these likely changes into account. Second, the temporal and spatial scale of the data may not always be sufficient to identify problems that occur at specific locations or during specific seasons. These issues are addressed below using data on trends of population and power generation as a basis for making projections of future water requirements.

Relating Water Use to Other Factors

Overall freshwater demand, over a broad geographic area, which consists of municipal and other uses such as industry, power generation, irrigation, etc., is generally more difficult to predict than municipal or urban water demand alone, which are relatively well characterized (e.g., in resources such as U.S. Army Corps of Engineers, 1998; Planning and Management Consultants, 2001). Overall water demand for the United States as an aggregate entity has been projected in many studies before, but not always very accurately (as discussed by Lins and Stakhiv, 1998). In the early part of this century, freshwater use was generally well correlated with population. However, in the past two decades, this relationship does not appear to have held: freshwater withdrawals have declined since 1985 even as the total population increased by 10 percent. Note that some of the decline can be attributed to an increase in other types of water supply such as saline water or reclaimed wastewater. In earlier studies (USGS, 1975; WRC, 1978; and other reports from 1968 to 1975 cited in Guldin, 1989, and in Lins and Stakhiv, 1998), projections of water demand made for the late 1990s covered a wide range, and most projections were substantially higher than actual withdrawals. Part of the reason for this inaccuracy was the assumption of increasing demand with increasing population. Although this trend may hold true in specific regions or metropolitan areas, it does not generally apply on the scale of a country or a state because most water is not used directly, but indirectly in electricity generation and agricultural, commercial, and industrial activity. These latter withdrawals are subject to changes due to technological and economic factors unrelated to population growth.

Of the older studies noted above, the Water Resources Council (WRC) report of 1978 (WRC, 1978) deserves special attention because of the relative accuracy of its projection that freshwater withdrawals would decline slightly from 1975 to 2000 from 338 billion gallons per day (bgd) (1.28×10^9 m^3/day) to 307 bgd (1.16×10^9 m^3/day). The actual freshwater withdrawals estimated by USGS for 2000 were 345 bgd (1.30×10^9 m^3/day) (Hutson *et al.,* 2004). The projection of a decline by WRC was calculated based on substantial reduction in manufacturing sector water withdrawal, a moderate reduction in electricity generation withdrawal, a small decline in agricultural withdrawal, and a moderate increase in domestic water withdrawal. Although the total withdrawals estimated by the WRC and USGS studies were similar, there are significant discrepancies between them in the estimates of water withdrawal by different sectors, most significantly in the areas of thermoelectric cooling and industrial and commercial water use, where the estimates differ by more than 50 percent. However, the essential element of the prediction from WRC was that withdrawals for most sectors would change only slightly. In fact, if the assumption of a significant decline in industrial water withdrawal had not been made, the overall projection may have been closer to the actual value of withdrawal estimated by the USGS in 2000. This prediction of no growth in withdrawal is noteworthy because it was made at a time when the water withdrawals in the preceding decades had been increasing steadily (Murray and Reeves, 1977), and other contemporaneous studies were anticipating a doubling of water withdrawal by the year 2000 or an even larger increase (as cited in Lins and Stakhiv, 1998). However, 1978 was the last year in which the federal government conducted a national scale assessment of water supply sustainability (GAO, 2003).

In years from 1975 to 2000 for which water withdrawal data are available at the aggregate level, substantial changes in the factors that influence water use occurred: the total population of the United States increased from 216 million to 281 million (U.S. Census Bureau, 2004); the gross domestic product increased from US$4.3 trillion to US$9.8 trillion (in 2000 dollars) (BEA, 2004); electricity production by utilities doubled from 1.92 million to 3.8 million gigawatt hours (EIA, 2003); and farm acreage decreased from 1.02 billion} acres (410 million hectares) in 1974 to 938 million acres (379 million hectares) in 2002 (USDA, 2004). Despite some changes that would suggest increases in water withdrawal over 1975 to 2000, particularly population and electricity production, withdrawals have remained essentially uniform, thus indicating greatly improved water use efficiency in many sectors of the economy.

Projecting Demand in 2025

A combination of data from 1975 and 1995 was used to project water requirements in the future. Potential increases in requirements of water were assumed to be largely controlled by changing demand due to population and electricity production increases. Other uses of water, such as irrigation and industrial and commercial use, are not considered to drive new demand, although they may change in response to demands from municipalities and electric utilities. Two approaches to calculating future water requirements for domestic and thermoelectric cooling may be taken: rates of use (such as per capita withdrawal for domestic use and water used per megawatt hour of electricity generation) can be assumed to remain at their current levels, even as the total population or total electricity generation increases (the "business-as-usual scenario"); or rates of water use can be assumed to exhibit trends of increasing efficiency, partly counteracting increasing electricity generation and domestic demands (the "improved efficiency scenario").

Depending on the type of water use and the region, either one or the other scenario may be more accurate. The business-as-usual scenario is appropriate if the improvements in efficiency have reached a maximum and further reductions in the rate of water use may not be possible. The improved efficiency scenario supposes that decreasing rates of water use in key sectors of the economy can continue. Evaluation of both scenarios provides the best judgment of the upper and lower bounds of regional water requirements.

To evaluate domestic water demand in 2025, it is estimated that the population in each county will exhibit the same decadal rate of growth that it did over 1990 to 2000. The change in population thus forecast for 2025 is shown in Figure 8. The total forecast population by this approach for the entire United States is 410 million, roughly equal to the high estimates of forecasts by the U.S. Census Bureau (Day, 2001). To the extent that these population estimates are on the high side, the water demands estimated in

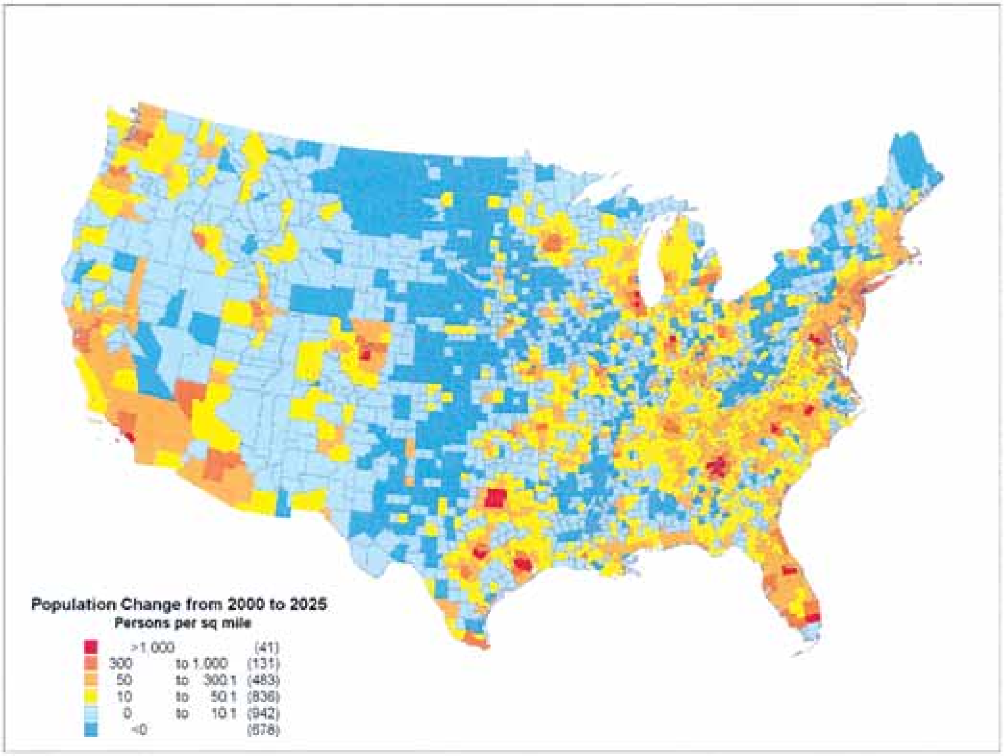

Figure 8. Change in Population Between 2000 and 2025. Based on historical population from U.S. Census Bureau (2004) and future projections as detailed in the text.

this work are conservatively high. If future regional trends in population growth are similar to trends in the recent past, some of the regions with the least amounts of available precipitation will experience the greatest increases in population.

The forecast growth of electricity generation over 2000 to 2025 at the census division level, where each census division comprises several states, is published by the Energy Information Administration (EIA, 2003). These projections are based on a comprehensive energy economic model of the United States and were used as provided by the EIA. More spatially resolved data were not available for these forecasts. For the purpose of estimating the power generation in 2025 at the county level using the EIA forecasts and 1995 county level data on electricity generation, four assumptions were made.

- The actual change from 1995 to 2000 was applied as reported at the state level to all counties within a state that had any form of power generation (hydroelectric or thermal).
- The forecast percent increase in generation from 2000 to 2025 was then applied to all counties within a census division that had any form of power generation (hydroelectric or thermal).
- Counties that have no generation at present were not allocated any new generation.
- All new generation was assumed to be thermoelectric.

These assumptions are known to have limits and, if additional data become available, may be revised in future studies or in more localized evaluations of water requirements. In the event that undeveloped renewable energy sources meet some of the increased electricity demand, the assumption of all new generation being thermoelectric is conservative from the water requirement standpoint. A map with the new thermoelectric generation by 2025 is shown in Figure 9. Areas with significant new power generation are expected to be in the Midwest, the Southeast, and the Southwest.

For estimating water withdrawals for the business-as-usual scenario, it was assumed that the irrigation, livestock, mining, industrial, and commercial water withdrawals were unchanged from their 1995 values. New domestic demand in 2025 was calculated by multiplying the projected 2025 population with the 1995 per capita withdrawal rates. New thermoelectric cooling water needs were based on the new generation multiplied by the rate of water use in that county. If a county did not have any thermoelectric generation in

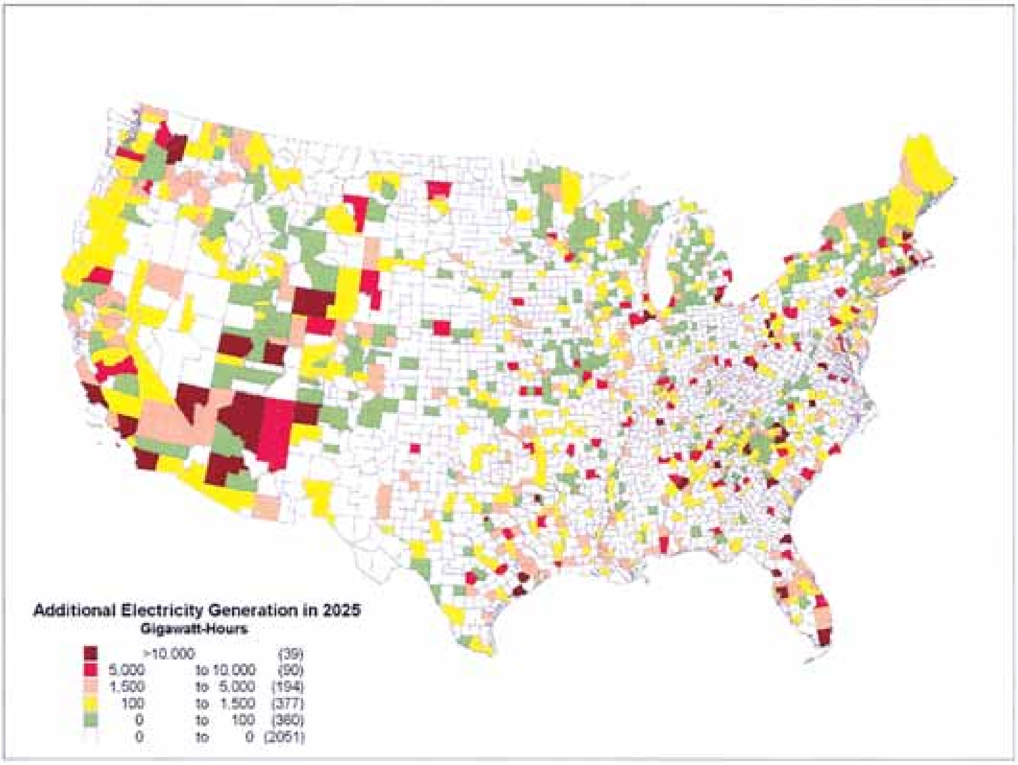

Figure 9. New Thermoelectric Generation Expected by 2025. Based on historical generation data from EIA (2003) and future projections as detailed in the text.

1995, the average rate of water withdrawal for that state was used instead. Using county specific values for the rates of water use permits consideration of the strong regional variability in rates of water use in making the 2025 projections. The change in water withdrawal requirements from 1995 to 2025, in inches per year, for the business-as-usual scenario is shown in Figure 10. Substantial increases in water withdrawal are noted in the Northeast and Southeast and major metropolitan areas throughout the rest of the country. Of course all increases in demand are not the same; an increase in withdrawal in an arid region may be much more difficult to meet than a similar increase in a region with greater water availability.

To calculate the water requirements for the increased efficiency scenario, it was assumed that the trends in rates of water withdrawal for domestic consumption and for thermoelectric cooling follow the same annual rates of change over 1995 to 2025 that they have exhibited over 1975 to 1995. Consistent databases for thermoelectric generation and domestic water use are only available at the USGS Water Resources Region (WRR) level from the WRC study of 1978. Hence, the annual percent change in rate of water use over 1975 to 1995 calculated at the WRR level and applied to all counties within that WRR was used to estimate rates of domestic and thermoelectric water use for 2025. The total withdrawal and the rate of water use (either per capita or per megawatt hour of electricity generation) for thermoelectric cooling and domestic use are presented in the appendix. Also calculated is the annual percent decrease in the rate of use at the WRR level. The decrease in water use per unit of energy generated, shown in Table A1 in the Appendix, is a result of improvement in technologies for generation and for cooling. Applying the same rate of decrease in the future implies that these technologies will continue to improve water use efficiency for cooling. Total water requirements in 2025 for the increased efficiency scenario were calculated by using 2025 estimated population and 2025 per capita domestic use (Table A2 in the Appendix), and by using 2025 new electricity generation and 2025 rate of cooling water use. An exception was made for the rate of cooling water use in the Pacific Northwest region, which showed a 9 percent annual increase from 1975 to 1995. For this region it was assumed that the rate of cooling water use would not change from 1995 to 2025 but remain at 1995 levels. All other water uses remained at their 1995 levels. A map of the change in water withdrawal requirements from 1995 for the increased efficiency scenario is shown in Figure 11. This map is drawn using the same colors and scales as used in the map for the business-as-

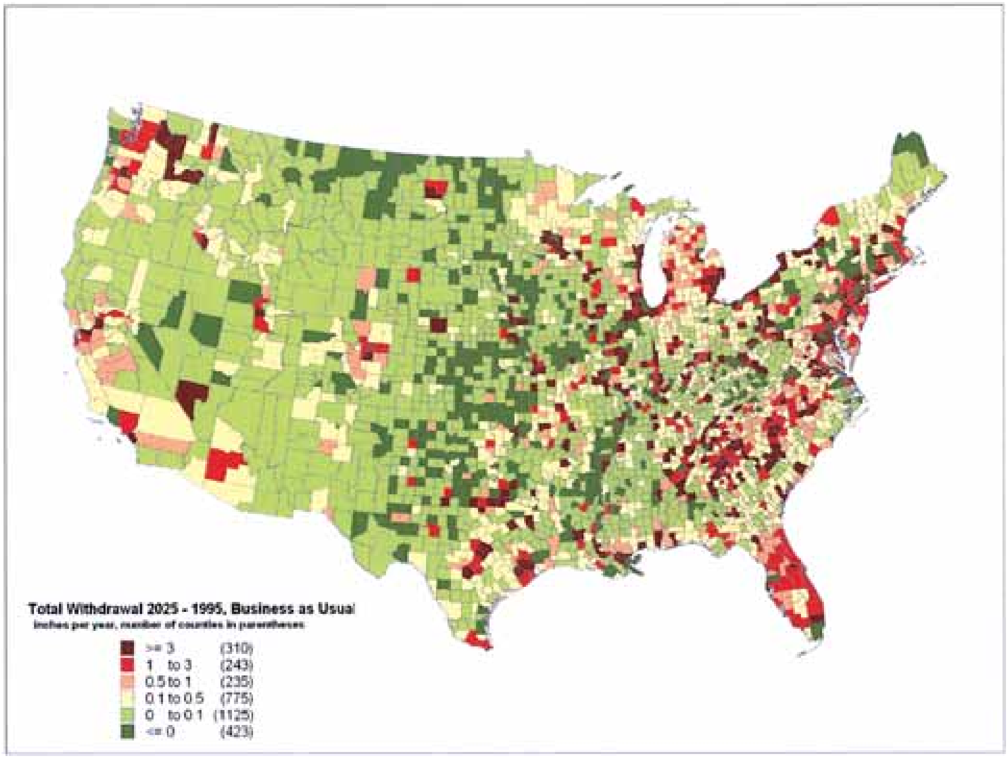

Figure 10. Business-as-usual Projections of County-wide Changes in Water Withdrawals from 1995 to 2025, Normalized to County Area and Presented in Inches per Year.

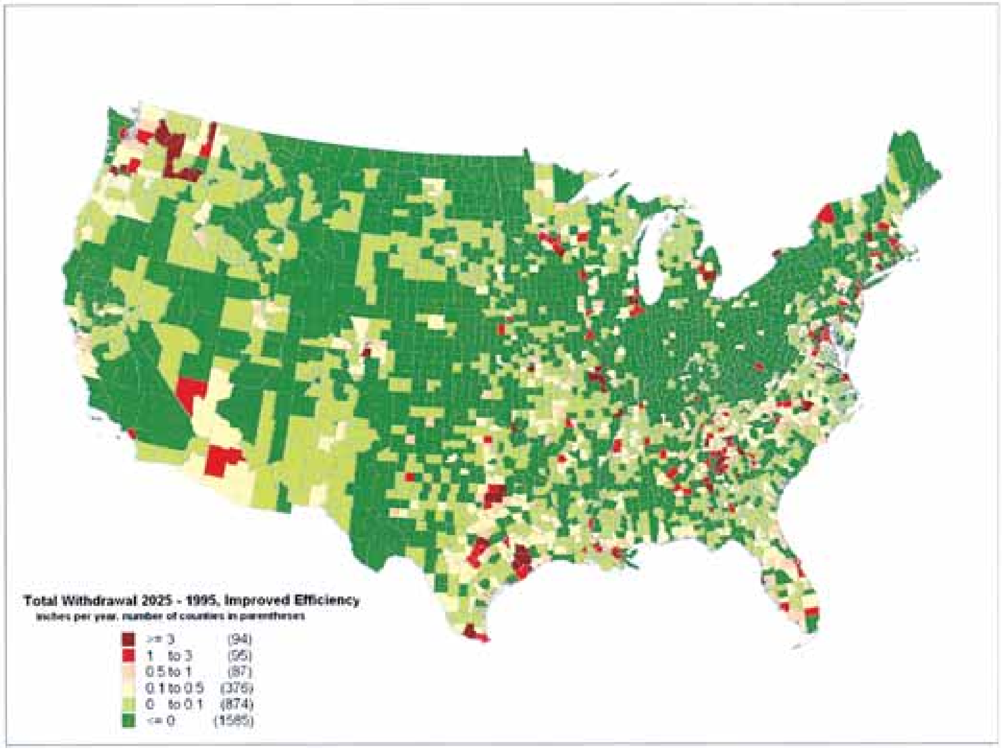

Figure 11. Changes in County-wide Total Freshwater Withdrawals from 1995 to 2025 under the Improved Efficiency Scenario, Normalized to County Area and Presented in Inches per Year.

usual scenario and shows the tremendous potential of ongoing trends in efficiency to ameliorate increased water requirements in most regions of the country. Despite the projected improvement in efficiency, some areas still exhibit substantial increases in water requirements. These include, for example, areas around Washington, D.C., New York, Atlanta, Miami, Houston, San Antonio, Dallas, Phoenix, Las Vegas, and eastern Washington.

The concept of increased efficiency of water use can also be applied to sectors other than domestic and thermoelectric use. However, in computing the rate of water use for sectors such as agricultural, commercial, and industrial use, because of the huge variety of crops, services, and products, it is not straightforward enough to determine a rate of water use per unit of production (such as water withdrawal per megawatt-hour of electricity produced). In practice, agricultural withdrawals have remained essentially uniform over 1975 to 1995, with different regions showing increases and decreases in water use per irrigated acre of land (see appendix). Commercial and industrial uses are relatively small components of the total withdrawals. Hence, it is reasonable to assume that changes in water requirements for these latter uses will not drive the water demand in the coming decades. This is not to say, however, that these withdrawals will remain constant. As pointed out earlier, estimates of requirements for 2025 do not necessarily imply that there will be an increase in the total water withdrawal; the new requirements are just as likely to be met through adjustment of uses by other sectors.

Estimate of Storage Needed by 2025

Analogous to the summer deficit computed for 1995 (Figure 6), the summer deficit corresponding to the 2025 business-as-usual withdrawals was computed using average 1934 to 2002 precipitation values. The change in summer deficit from 1995 to 2025 is an indication of the new stored water requirements from 1995 levels and is shown in Figure 12. The map shows that water sustainability concerns are not limited to the western United States, and many regions in the eastern United States may require new water supplies during the summer months or modification of existing patterns of use.

Comparison with Previously Published Projections

The projected future withdrawals in this study can be compared with 10-year studies performed by the U.S. Department of Agriculture (USDA) that project

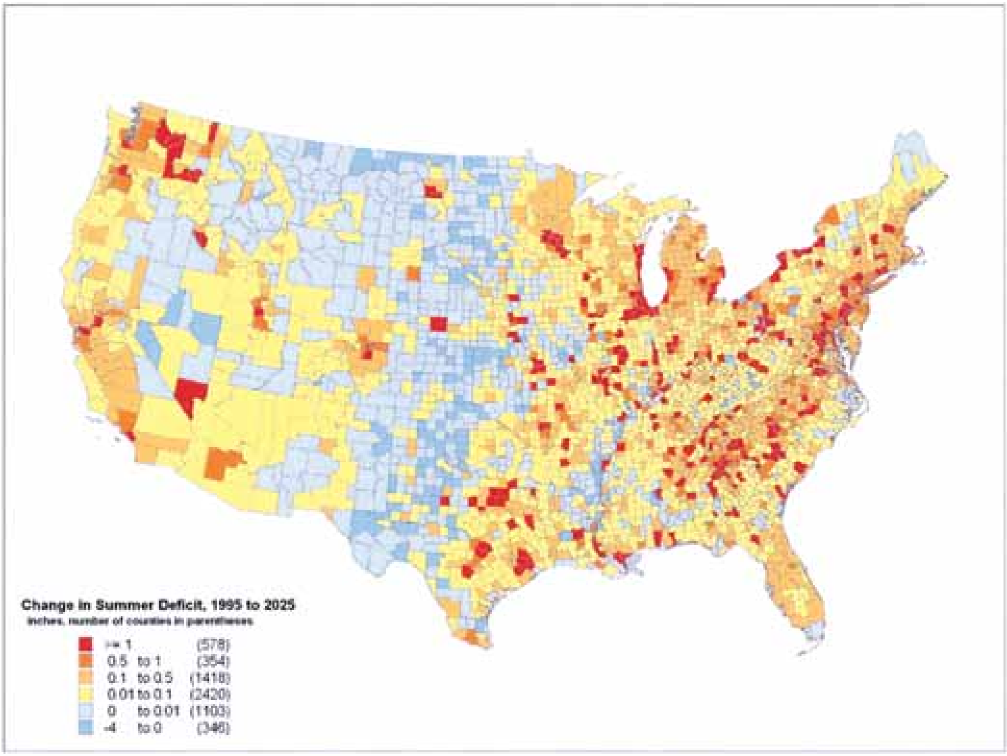

Figure 12. The Change in Summer Deficit from 1995 to 2025,
for the Business-as-usual Scenario, in Inches per Year.

withdrawals to 2040 (Guldin, 1989; Brown, 1999), *albeit* at a much coarser spatial scale (projections were made at the WRR level). At present the USDA is the only agency of government that makes national-scale forecasts at 10-year intervals, as part of its mandate under the Resources Protection Act (Guldin, 1989). The WRC, which was used as the data source for evaluating changes in the rate of water use by region, ceased to exist in 1981.

Using the 1985 USGS dataset as a starting point, Guldin (1989) estimated increases in practically all types of water withdrawal in the future. The rates of increase varied by sector and were applied nationally. Total withdrawals were expected to increase to 461 bgd (1.74 x 10^9 m^3/day) in 2020 and to 495 bgd (1.87 x 10^9 m^3/day) in 2030 (i.e., respectively increasing 34 percent and 43 percent over 1995 levels). An effort was also made in this study to relate the withdrawals and consumptive use to regional water budgets. Estimates of necessary flows required to maintain adequate instream conditions for maintaining optimal habitat for fish and wildlife were obtained from WRC (1978). Future outflows were calculated by subtracting the projected consumptive uses from the renewable water supply for dry and wet years. A region was in surplus or deficit depending on whether the outflow was higher or lower than the instream flow requirement. A key feature of the required instream flow estimates is that areas with relatively high quantities of renewable water supply also have high instream flow requirements. Based on this analysis, deficits in instream flows currently occur in the wet and dry seasons in the Rio Grande, the upper Colorado, and the lower Colorado regions. Future deficits are likely to occur in the Lower Mississippi region, the Great Basin, and California, particularly in dry years.

In the Brown (1999) water demand projections for the USDA, the 1995 USGS data were used as the basis, applying national trends in rates of water use in the thermoelectric, domestic, livestock, and industrial and commercial use. Irrigation withdrawal change was assumed to be more region specific, with irrigation acreage change defined at the WRR level and the change in the rate of application of water applied defined separately for the eastern and western United States. Total withdrawals were projected by Brown (1999) to be from 350 to 357 bgd (1.32 x 10^9 1.35 x 10^9 m^3/day) in 2020 and 2030, respectively, for the middle range of population growth, 2 to 4 percent higher than 1995 levels, and therefore represents a significant reduction from the Guldin (1989) estimate. Table 1 compares the Guldin (1989) and Brown (1999) estimates with those obtained in this study. Population growth was a factor in the calculations as well by normalizing the water use in different sectors to the population, for example as livestock withdrawal per capita. Using these assumptions, Brown (1999) found that for low population growth (9 percent growth from 1995 to 2040), withdrawal would be expected to decrease by about 8 percent from 1995 levels, driven primarily by reductions in thermoelectric withdrawal and with withdrawal for other uses remaining roughly uniform. Alternatively, for the high population growth scenario (74 percent growth from 1995 to 2040), the total withdrawal would be expected to increase by 25 percent from 1995 levels, driven by increases in all sectors other than irrigation. Individual WRRs exhibit different patterns of increases and decreases that are not discussed here. The approach for estimating withdrawal described here is broadly similar to that used by Guldin (1989) and Brown (1999), except that more region specific estimates of change in rates of use have been used in this study (at the WRR level rather than the national level) and that change is assumed to be driven only by domestic and thermoelectric use. However, the main differences from the USDA studies and the one described here is the representation of water use at far greater resolution (at the county versus WRR level) and the incorporation of key hydrologic factors in estimating the extent of water use compared to available precipitation.

TABLE 1. Total Annual Freshwater Withdrawal in the Continental United States, in Billion Gallons Per Day, From Different Studies.

	Study		
Year	**Guldin, 1989**	**Brown, 1999**	**This Report**
2020	461	349[1]	
2025	–	–	451[2] 330[3]
2030	495	356[1]	

[1] For middle range of population growth.
[2] Business-as-usual scenario.
[3] Improved efficiency scenario.

Although the process of estimating future water withdrawals is uncertain, it can still be applied to paint a general picture of what the future may look like if current trends continue to 2025. Consideration of past improvements in water use efficiency can also be used to develop a different picture of withdrawals where factors that lead to the increase of water withdrawal are countered by improvement in the rate of water use. These two alternative scenarios were calculated using the best information currently available to bracket the likely future range of water withdrawals. Used in conjunction with climatic factors, this approach can be used to develop an understanding of the potential vulnerability of water resources across the United States.

Potential Impacts of Climate Change

The potential impact of climate change on water resources at the local, national, and continental scales has been evaluated extensively, both qualitatively and quantitatively; although the focus of some of the studies is on extreme events such as flooding that may be caused by higher intensity rainfall and hurricanes, many have focused on water supply (e.g., Boland, 1997; Vogel, 1997; Arnell, 1999; Strzepek, 1999; Blake *et al.,* 2000; Gleick, 2000; Hurd *et al.,* 2000; Murdoch *et al.,* 2000; and Vorosmarty *et al.,* 2000). The majority of studies of future water resources' sustainability have considered climate change as the principal driving force. Climate change, with implied changes in temperature and precipitation, may have a major effect on water resources. In fact, it is not an overstatement to say that changes in water resources, with consequent effects on agriculture and other areas of economic activity, are potentially among the most critical effects of climate change.

However, precipitation estimates from different global general circulation models vary widely, with both increases and decreases being indicated in the same part of the country (based on comparison of model output data obtained from Hulme *et al.,* 2000). Given this uncertainty in model predictions with respect to precipitation, quantitative assessments of the impacts of climate change on water resources at the county-level resolution were beyond the scope of the present study. To the extent, however, that worst-case scenarios are the focus of studies of water resources impacts, it is possible to conclude qualitatively that areas of the United States that are likely to be water stressed in the absence of climate change, as presented above, are going to be even more vulnerable in the event of climate change leading to reduced precipitation.

CONCLUSIONS

The most recent water use and climatic information was used to put together a national scale picture of water withdrawals for human use and its relation to total renewable water availability. According to the most recent data available for the United States, agricultural withdrawal and thermoelectric cooling withdrawal are the major components of total freshwater withdrawal (40 percent and 39 percent, respectively). Of these two categories of withdrawals, agricultural water is largely used consumptively, and on a national basis, 82 percent of the total consumptive use is for agriculture, in comparison with 3 percent of total consumptive use for thermoelectric cooling. Public domestic withdrawal and consumptive use is about 7 percent of the total. Review of water use data from 1975 to 2000 shows virtually no change in the total national freshwater withdrawal despite significant population growth and electricity generation growth. Freshwater withdrawal for irrigation has remained relatively constant, and land under irrigation has declined by about 10 percent. The improved efficiency of water use for electricity generation is notable: a doubling in generation over 1975 to 2000 was accompanied by practically no change in freshwater withdrawal. Using the annual water withdrawal, an approach was developed to estimate the withdrawal during the warm summer months and estimated the volume of water that is supplied from stored sources. For unusually dry years, the summer deficit can be substantial over much of the United States, including areas that are not normally thought of as water-deficient.

Future water requirements for the United States, at the spatial resolution of counties, were estimated using population growth in the United States over 2000 to 2025, extrapolated from trends over 1990 to 2000, and electricity demand increases over 2000 to 2025, forecast by the Department of Energy. Two scenarios were studied: a business-as-usual scenario in which the rates of water use remain at their 1995 values over 2000 to 2025 and an improved efficiency scenario in which there are annual improvements in water use efficiency (based on 1975 to 1995 data). These were used to estimate future requirements. The estimates show several areas of the United States, notably in the Southwest, as being likely to have significant new requirements with the business-as-usual scenario, under the condition of average water availability. These new requirements could be substantially eliminated when estimates were performed using the improved efficiency scenario, thus indicating the key role of water use efficiency in meeting future requirements. It is likely that no matter what future water withdrawals are, water sustainability constraints will emerge not during average flow years, but during years of below-normal precipitation. However, pressure for supplies during average rainfall years is a strong indicator of the potential of susceptibility when rainfall is below average.

It is important to place this study in the context of the substantial body of existing literature dealing with the forecasting of water resources sustainability. By limiting this study to using available national-scale data at the finest resolution possible, a framework was created for evaluating water sustainability at the county level. Although water use forecasts for the coming decades are available and others have defined and used the concept of sustainability, this study is unique in its spatial detail, approximation of potential storage deficits, and consideration of future demands, particularly for electric generation. The assumptions that are used in this framework (i.e., the approach to computing available precipitation, the distribution of water use in the summer months, the scenarios used to project future withdrawals) can all be modified and the maps updated should more appropriate data become available. It should also be pointed out that there are extensive ongoing efforts to monitor and prepare for drought on a national scale (e.g., the National Drought Mitigation Center; NDMC, 2004) that can be thought of as a complement to this study. For example, it is stated that about 38 states in the United States have or are developing a drought management plan. Drought monitoring and response studies are, in effect, short term emergency management plans on the order of months, designed to curtail use of water under special circumstances, usually with significant economic and/or social disruption. A longer term view over decades, such as that presented here, provides an opportunity for actually modifying patterns of water use such that reduced supplies are not economically or otherwise disruptive. This may mean focusing on the development of new supplies or the development of new technologies that reduce water use. The latter is of particular interest to the thermoelectric generators that must focus on identifying and evaluating technologies that use less water for cooling. There are also disadvantages to approaching the water sustainability problem at the national scale. In particular, not all types of data, such as storage, local water regulations, and water rights information, are available in a consistent format. Furthermore, for some types of large withdrawals, the county level may be too coarse a resolution to address more local impacts. Finally, a significant part of the national water use database is comprised of estimates of use rather than actual data, and errors and/or uncertainties in the database may propagate through the analysis presented here.

This study constitutes a step toward developing a comprehensive assessment of the state of the nation's water sustainability, although additional information is especially needed in three areas: instream use requirements to maintain optimal habitat and beneficial uses; water storage and withdrawal capacity available; and, finally, more temporally detailed patterns of water use. Instream flow requirements were last comprehensively assessed nationally at the water resources region level in the late 1970s. These data need to be updated and estimates provided at a greater spatial resolution. Renewable water storage (in snowpack, surface water reservoirs or lakes, and ground water) and the means to access them are a critical component of maintaining supply during the dry months of the year, but this information is not catalogued nationally. The USGS reports annual data on withdrawal, although it is widely known that water shortages are most keenly felt in the dry months. Future versions of the database must consider the inclusion of more temporal detail on water use such that deficits in the summer months (as estimated in this report) can be computed more accurately. From the standpoint of thermoelectric generation, this study finds that many power plants will have to be located in water short areas, and a comprehensive evaluation of the tradeoffs associated with using less or no water must be performed.

APPENDIX
EVALUATION OF WATER USE TRENDS BETWEEN 1975 AND 1995.

TABLE A1. Change in Thermoelectric Cooling Freshwater Withdrawal From 1975 to 1995.

HUC-2 Code	Water Resources Region	Thermo-electric Generation (gwh) 1975	Freshwater Withdrawal (mgd) 1975	Thermo-electric Generation (gwh) 1995	Freshwater Withdrawal (mgd) 1995	Withdrawal (thousand gallons/ mwh) 1975	Withdrawal (thousand gallons/ Mwh) 1995	Annual Percent Decrease in Withdrawal Rate	Withdrawal Rate Projected to 2025
1	New England	64,437	1,900	84,578	1,670	29	20	2.0	10.8
2	Middle Atlantic	195,067	14,000	258,586	12,664	72	49	1.9	27.6
3	South Atlantic Gulf	220,101	18,000	504,529	19,703	82	39	3.6	12.9
4	Great Lakes	182,992	25,000	218,588	22,787	137	104	1.3	69.5
5	Ohio	299,003	27,000	451,333	22,622	90	50	2.9	20.7
6	Tennessee	48,763	8,700	50,040	4,910	178	98	2.9	40.0
7	Upper Mississippi	112,704	13,000	211,119	19,070	115	90	1.2	62.6
8	Lower Mississippi	53,363	6,000	78,133	6,736	112	86	1.3	57.9
9	Souris-Red-Rainy	956	190	396	38	199	97	3.5	33.0
10	Missouri	55,851	4,200	167,181	8,807	75	53	1.8	30.9
11	Arkansas-White Red	65,755	2,800	143,014	4,203	43	29	1.8	16.8
12	Texas-Gulf	122,873	7,600	224,055	7,696	62	34	2.9	14.2
13	Rio-Grande	10,638	28	7,779	18	3	2	0.6	1.9
14	Upper Colorado	22,545	160	77,202	127	7	2	7.1	0.2
15	Lower Colorado	23,762	150	62,360	64	6	1	8.7	0.1
16	Great Basin	3,083	83	1,6291	24	27	1	13.5	0.0
17	Pacific Northwest	9,602	36	16,961	385	4	23	-9.4	338.1
18	California	84,763	1,500	76,008	211	18	3	8.9	0.2
19	Alaska	1,116	21	3,770	31	19	8	4.0	2.4
20	Hawaii	5,167	170	6,366	67	33	11	5.5	1.9
21	Caribbean	9,937	0	16,534	4	0	0	-	-
	US Total	1,592,478	130,538	2,674,822	131,837				

Notes: gwh = gigawatt hours, mgd = million gallons per day, and Mwh = megawatt hour.

TABLE A-2. Change in Domestic Water Withdrawal 1975-1995.

HUC-2 Code	Water Resources Region	Public Population Served in Thousands, 1975	Domestic Use Public Supply (mgd), 1975	Public Population Served in Thousands, 1995	Domestic Use Public Supply (mgd), 1995	Public Per Capita Withdrawal, 1975	Public Per Capita Withdrawal, 1995	Annual Percent Decrease	Withdrawal Per Capita Projected to 2025
1	New England	64,437	1,900	84,578	1,670	29	20	2.0	10.8
1	New England	10,000	830	10,426	717	83	69	0.9	52
2	Middle Atlantic	34,800	3,700	35,684	3,344	106	94	0.6	78
3	South Atlantic Gulf	18,000	2,000	30,774	3,146	111	102	0.4	90
4	Great Lakes	18,000	1,800	16,963	1,400	100	83	1.0	62
5	Ohio	15,400	1,600	17,990	1,138	104	63	2.5	30
6	Tennessee	2,370	210	2,620	209	89	80	0.5	68
7	Upper Mississippi	16,600	2,100	17,974	1,454	127	81	2.2	41
8	Lower Mississippi	5,300	590	6,328	703	111	111	0.0	111
9	Souris-Red-Rainy	366	41	446	26	112	59	3.1	23
10	Missouri	6,760	870	8,978	966	129	108	0.9	82
11	Arkansas-White-Red	5,900	670	7,681	767	114	100	0.6	82
12	Texas-Gulf	8,240	930	15,690	2,158	113	138	-1.0	185
13	Rio-Grande	1,470	250	2,297	340	170	148	0.7	120
14	Upper Colorado	309	67	547	85	217	154	1.7	93
15	Lower Colorado	2,230	420	4,925	755	188	153	1.0	112
16	Great Basin	1,200	330	2,280	417	275	183	2.0	99
17	Pacific Northwest	4,810	720	7,476	1,016	150	136	0.5	118
18	California	19,900	3,000	30,445	3,704	151	122	1.1	88
19	Alaska	184	80	381	38	435	99	7.2	11
20	Hawaii	808	150	1,122	131	186	117	2.3	58
21	Caribbean	2,320	270	3,585	173	116	48	4.3	13
	U.S. Total	174,967	20,628	224,609	22,685				

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