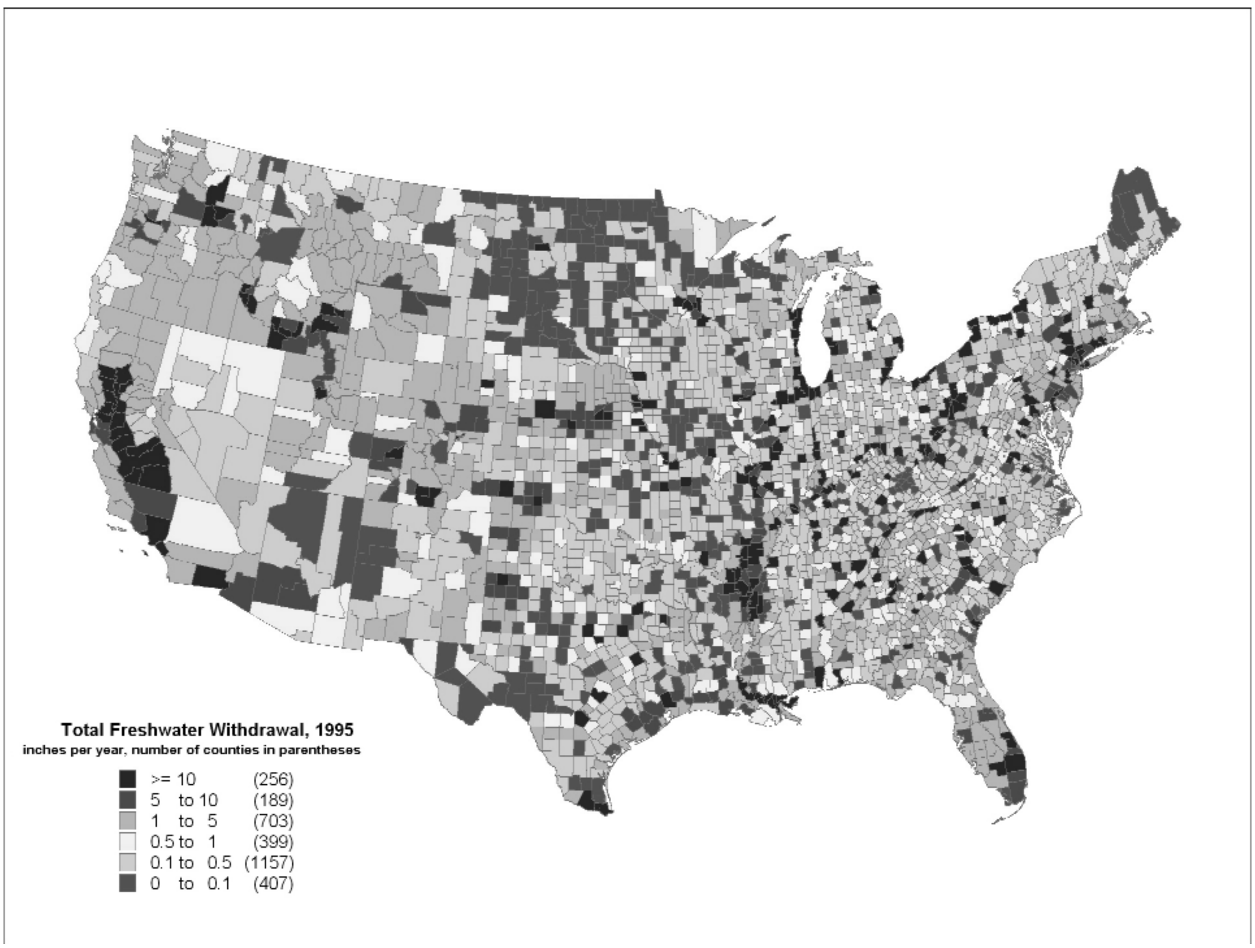
A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation

Technical Report



A Survey of Water Use and Sustainability in the United States With a Focus on Power Generation

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Topical Report, November 2003

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REPORT SUMMARY

EPRI has identified water resource sustainability and its relation to electric power as one of the key challenges within EPRI's Electricity Technology Roadmap. This report presents an overview of present and future freshwater availability, and generation demand for fresh water in the United States. The report takes a first step toward development of a comprehensive framework for evaluating possible impacts of water supply limitations on electric power generation and management approaches to limiting these impacts. Information provided will be of particular value to power generation and delivery managers and planners as well as government energy and water resource managers and regulators.

Background

Several years ago, EPRI identified water availability as a major factor influencing future power development both nationally and internationally. As a result, EPRI developed a water sustainability module for the EPRI Electricity Technology Roadmap. At the same time, with the support of members in the Total Maximum Daily Load (TMDL), Watershed and Ecosystem Issues Program, EPRI initiated research to develop a comprehensive framework to evaluate potential power industry susceptibility to water availability shortages.

Objective

- To survey present and future freshwater availability, and generation demand for freshwater in the United States.

- To initiate development of a comprehensive framework for evaluating possible impacts of water supply limitations on electric power generation and management approaches to limiting such impacts.

Approach

Investigators computed and mapped various metrics characterizing water use. Based on these metrics, they calculated and mapped two composite indices—a Water Supply Sustainability Index and a Thermoelectric Cooling Constraint Index. The first index identifies regions of the country where water sustainability concerns are likely to be most severe, while the second identifies regions where constraints on cooling water withdrawals for power generation are expected to be significant. These indices can be used to identify areas for more detailed analysis. A case study for the Phoenix, Arizona, area is included in this report.

Results

Based on the metrics used and indices calculated, areas vulnerable to water availability shortages and water-induced constraints on electric power generation are not limited to the arid and semi-arid West and Southwest, but occur throughout the United States. Vulnerability will increase over the next quarter of a century as a result of greater demands for fresh water associated with population growth. Climate change and growing concerns about environmental protection may also exacerbate the situation.

Although the maps of water sustainability created for this study use the best available information today, there is a need for improved data, particularly in the following areas: 1) instream flow requirements for ecological protection, 2) water (reservoir and groundwater) storage and withdrawal capacity; and 3) fine temporal resolution of water use. From the standpoint of thermoelectric generation, the study finds that many power plants will need to be located in areas facing water shortages and will thus require comprehensive evaluation of the tradeoffs in using less or no water.

EPRI Perspective

EPRI's Electricity Technology Roadmap provides a long-term (20-50 year) global vision for a robust and environmentally sustainable energy future. Societal and economic health are highly dependent on the availability of electric power, while electric power generation and delivery are, in turn, highly dependent on the availability of water. To address the challenge of energy/water sustainability, EPRI has created a Water Sustainability Initiative and has incorporated water sustainability research into its base research program within the Water and Ecosystems Area. EPRI is working cooperatively with the U.S. Department of Energy (USDOE) and USDOE national laboratories to create a national research program that will address the energy/water nexus. In partnership with Public Service Company of New Mexico and Los Alamos National Laboratory, EPRI has created the ZeroNet Water-Energy Research Initiative, a comprehensive integrated research program, to meet New Mexico’s increasing electric power demand without increasing net fresh water withdrawals for power plant cooling. Finally, EPRI is working with the California Energy Commission and Lawrence Livermore National Laboratory to organize a workshop to identify major energy/water sustainability issues in California.

Keywords

Water Availability
Water Sustainability
Water Use
Water Demand
Electric Power
Forecasts

ABSTRACT

This study presents an assessment of current and future water withdrawal requirements compared with water availability, resolved at the level of counties across the continental United States. Various metrics characterizing water use are computed and mapped, representing water availability, the extent of water resources development, sustainable groundwater use, environmental constraints on water withdrawal, projected growth in water demand and power generation, and growth in demand for stored water.

Based on the metrics of water use, EPRI proposes two composite indices—a Water Supply Sustainability Index and a Thermoelectric Cooling Constraint Index. The first index identifies regions of the country where water sustainability concerns are likely to be most severe, and the second identifies regions where constraints on cooling water withdrawals for power generation are expected to be significant. Maps of these indices can provide the basis for further study at local levels.

This report presents a case study for the Phoenix, Arizona, area, which is expected to continue unsustainable groundwater withdrawals into the foreseeable future, despite extensive efforts to manage water use, develop new water sources, and conserve water. In addition to the physical limits associated with water availability because of growing demands, this case study reveals the significance of limits imposed by the existing legal and institutional infrastructure. The study represents an important step toward developing a comprehensive assessment of the nation's water resources, one that has not been conducted for the past 25 years. It also takes an important step toward evaluating the possible impacts of water supply limitations on thermoelectric power generation.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 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 over the next 25 years, and to assess the water sources that can meet these withdrawal requirements. A specific objective of this report is to focus on the potential increases in demand for cooling water for thermoelectric power generation, and to identify regions where water supply scarcity may become a constraint on power generation capacity. This study was motivated by a general awareness that in coming decades demand increases associated with 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), and in light of the current concern with water shortages, the analysis presented in this report is timely. This analysis builds upon and extends an earlier analysis of water sustainability in the US published by EPRI (2002a).

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

In Chapter 2 of this report, we present an overview of current water use and the forces that exert strong influences on water use for the continental US (such as climate, agricultural activity, and power generation) based on a synthesis of data from different government agencies. Maps for the entire US, with data at the county level (3,114 counties in 48 states) are presented for 1995, the most current year for which national-scale water use data have been compiled. Water use data are compared with water availability to develop an understanding of the sustainability of water use under current conditions.

In Chapter 3 we estimate *potential* water requirements in 2025, at the county level across the US. These estimates are based on scenarios where increases in population and electricity generation drive increases in water demand, and other uses of water (agricultural, industrial, commercial, and mining) are assumed to remain essentially unchanged. Two alternate scenarios are presented assuming either that rates of water use remain at their current levels, or that the trends in rates of use over the period from 1975-2025 will be maintained over the next 25 years. In all likelihood, the estimated potential water demand for either scenario for 2025 will not be the actual withdrawal, because there will be adjustments among different users of water, such that in the face of scarcity, certain uses of water will become more efficient or be curtailed in favor of other uses. As discussed later in the report, predictions of future water withdrawals based on an extrapolation of current trends, have often been extremely inaccurate, and are perhaps inappropriate given the tremendous uncertainties in the factors that affect water use in a region. However, key ratios based on potential water demand for 2025, such as the percentage change from current conditions, and potential demand as a percentage of available water in a region, can be used to identify areas where potential conflicts and the pressures for adjustments in water use will be greatest.

We propose an index of water supply sustainability using metrics representing information in six different categories: water availability, extent of water resources development, sustainable groundwater use, environmental constraints on withdrawal, projected growth in water demand and power generation, and growth in demand for stored water. Using this index we identify regions across the country where water sustainability is likely to become an important issue in the future. Using the water supply sustainability index in conjunction with the forecast increases in electricity generation, we also develop an additional index, the Thermoelectric Cooling Constraint Index to map areas where water availability may become a constraint for the location of new power generation. This synthesis of data is presented in Chapter 4.

The scale of the data used in Chapters 2 to 4 provides a national snapshot on an annual average basis, but does not permit a detailed assessment of the future directions of water sustainability in any one region, particularly in the presence of institutional and legal mechanisms that define water use. To do this, in Chapter 5 we assess water sustainability in one of the most water-short and fast-growing regions in the US, the Phoenix, Arizona, metropolitan area.

The potential role of climate change on water resources has been widely discussed. Based on available information on model-predicted patterns of temperature and precipitation change, we were unable to perform a quantitative analysis in the manner described in Chapter 3 and 4. Instead, a short description of the water resources assessment in the context of climate change is presented in Chapter 6.

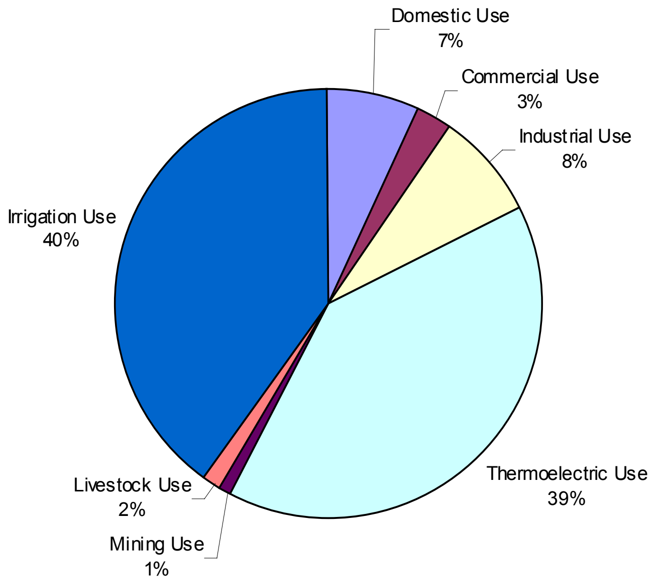
The principal findings of this study, such as the identification of regions with potential for water sustainability concerns, the implications for existing and new thermoelectric power generation facilities, and the benefits of conducting a detailed study water sustainability at a regional or local scale are summarized in Chapter 7. Future data needs for enhancing our understanding of water sustainability are also discussed.

2
WATER USE AND SUSTAINABILITY IN THE U.S. IN 1995

In this chapter we present summary graphs and maps providing a comprehensive picture of the nature of water use in the US, and of the principal forces that control water use, such as population, climate, agricultural activity, and power generation. The most comprehensive data on water use in the US is collected every 5 years by the US Geological Survey (USGS) as part of the National Water Use Information Program. These surveys were first conducted in 1950, and the most recent survey that is available is for 1995 (USGS, 1998; USGS, 2002a). Work on the 2000 survey is ongoing at the time of this writing. This data gathering effort obtains information on surface water and groundwater withdrawals and consumptive use, and identifies use by six major categories: public and domestic water supply, commercial, industrial, mining, agricultural, and thermoelectric cooling (including fossil-fuel and nuclear power generation). In the terminology of the USGS, these are termed “offstream” uses, as opposed to “instream” uses for hydroelectric power generation. Instream uses for non-human, environmental purposes are not cataloged by the USGS. This report is primarily focused on offstream freshwater use. Water use data from the USGS were supplemented by other data on climate from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA), on population from the US Census Bureau, on electricity generation from the Department of Energy, and on agricultural activity and land use from the US Department of Agriculture. All national scale maps in this report are presented with data resolved to the county-level. This was the highest resolution of all the publicly available national-scale datasets. The USGS water use database also includes information at the watershed level (Hydrologic Unit Code, level 8), but was not used in this study to provide consistency with the other databases.

On a national aggregate basis, Figure 2-1 (a) and (b) show the offstream withdrawal and consumptive use of freshwater for each of the six major categories described above. Agricultural and cooling water withdrawals are the dominant components of the total water withdrawal nationwide (40% and 39%, 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 of the total consumptive use (3%). Irrigation is the most significant consumptive user of water (82%). Consumptive water use for domestic purposes is the second most significant use (7%).

a) Freshwater Withdrawal



b) Freshwater Consumptive Use

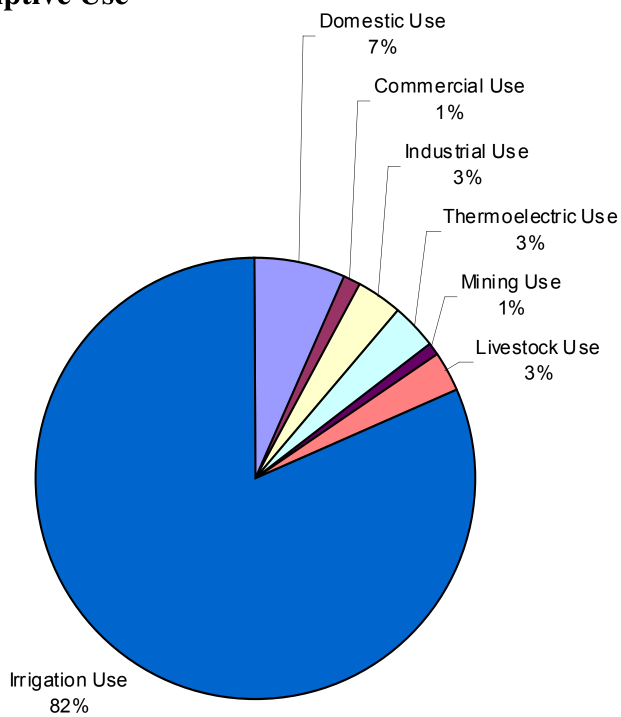


Figure 2-1
(a) Offstream freshwater withdrawal and use by major sectors of the economy, and (b) the consumptive use of water by major sectors of the economy. The total offstream freshwater withdrawal is 342 billion gallons per day and the total consumptive use is about 100 billion gallons per day.

Before we discuss national patterns of water use, it is important to briefly describe the climatic context in which this use takes place. In a given region, 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 groundwater or moves as runoff into surface water bodies. For the purpose of this discussion we consider that precipitation that is not lost to evapotranspiration (henceforth termed available precipitation) can be used for other purposes, and is an approximate measure of available renewable water in a region. We calculate this as the precipitation minus potential evapotranspiration (PET)[1] for each month, and then sum the net values for the entire year. For months where the PET exceeds precipitation, the net addition to the available water for that month is zero, to avoid counting unavailable water. The approach used to calculate available precipitation is shown for an example county in Florida (Broward County) in Figure 2-2, using precipitation and PET data averaged over 1934-2002.

Precipitation and PET data averaged from 1934 to 2002 for the 344 climate divisions covering the continental US were used to calculate the available precipitation, in inches per year, across the US (shown in Figure 2-3). This map shows data at the county level that was estimated from the climate divisions. The location of the centroid of the counties was used to assign counties to a climate division. Data are presented at the county level in Figure 2-3 to be consistent with other maps that follow. Much of the western US, except for some coastal areas, has far lower water availability than the eastern US. In the eastern US, the water availability is lower in regions with higher PET, such as south Florida.

The three principal drivers of water use, population density, irrigated land, and thermoelectric power generation are shown for the US in Figure 2-4 (a)-(c). Major centers of populations are in the northeastern US, along the Atlantic and Pacific coasts, and in the Great Lakes region. The fraction of total land area that is irrigated is high along the Lower Mississippi River, in Florida, Nebraska, Kansas, northern and southern Texas, and in California’s Central Valley. Thermoelectric power generation facilities are spread throughout the eastern US. In the western US, thermoelectric generation is concentrated in the southwestern states, where large coal-fired and nuclear facilities have been sited.

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[1] Potential evapotranspiration (PET) is a theoretical estimate of the amount of water that can be lost by evapotranspiration. One of the commonly used approaches for estimating PET calculates it as a function of temperature and hours of sunlight at a given location (Huang et al., 1996). There is another term that is commonly used in the literature, actual evapotranspiration (AET), which is the PET multiplied by a factor to account for local land cover conditions.

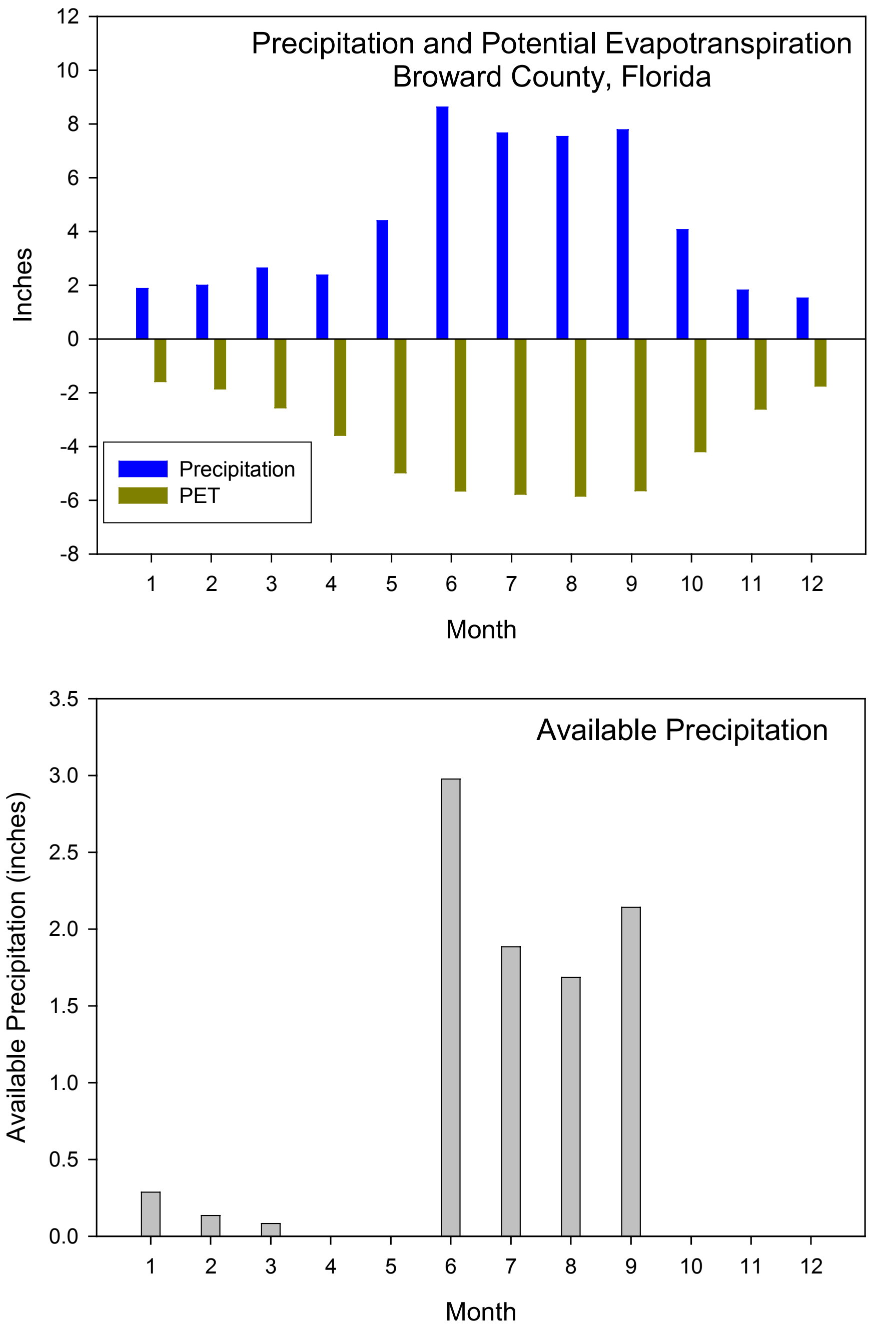


Figure 2-2
(a) Precipitation and potential evapotranspiration for Broward County, Florida, average of 1934-2002 data, and (b) the available precipitation for each month of the year as defined in the text.

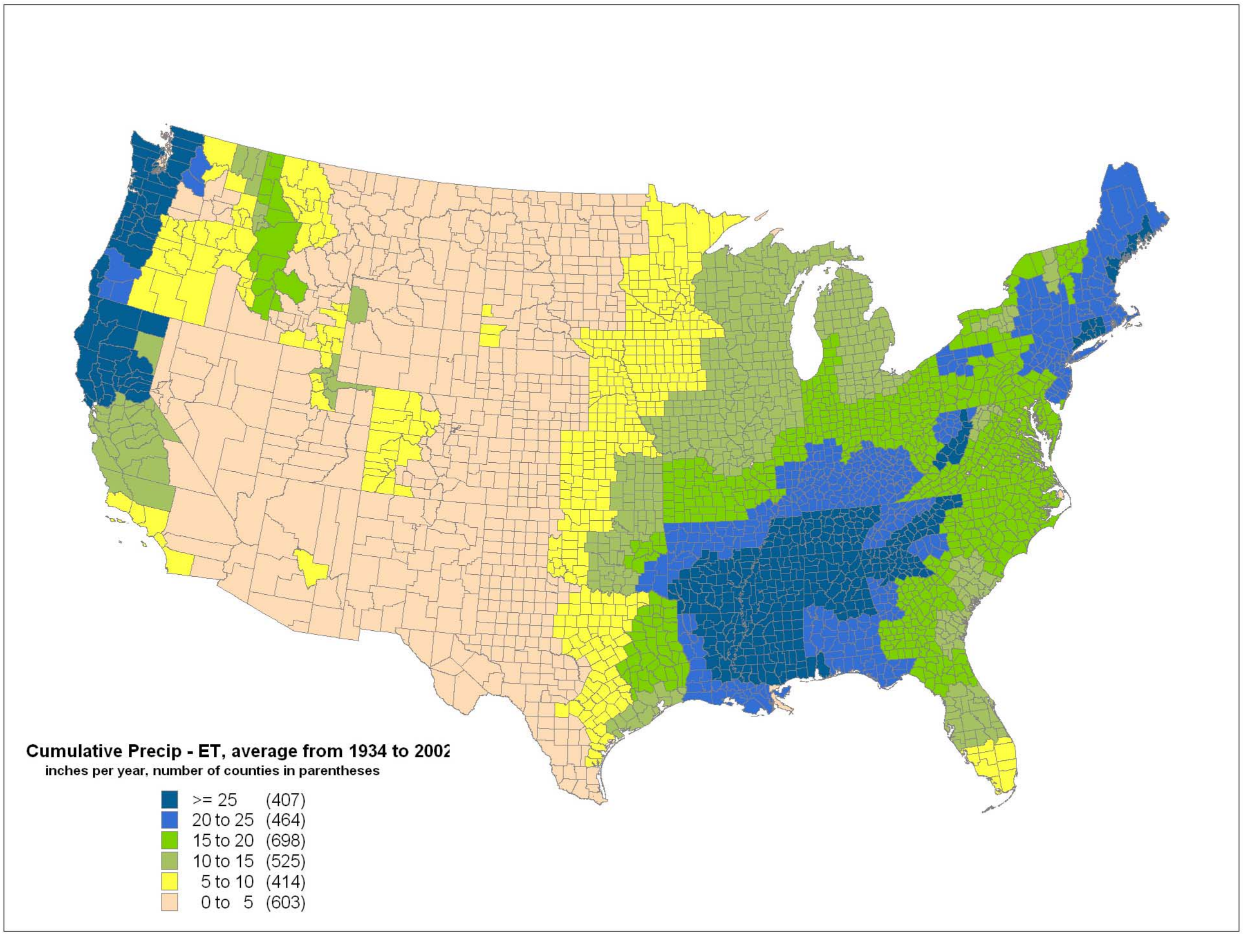


Figure 2-3
Available precipitation (difference between monthly precipitation and potential evapotranspiration, sum of months with non-zero values, as defined in the text) across the US, based on 1934-2002 average data at the climate division level.

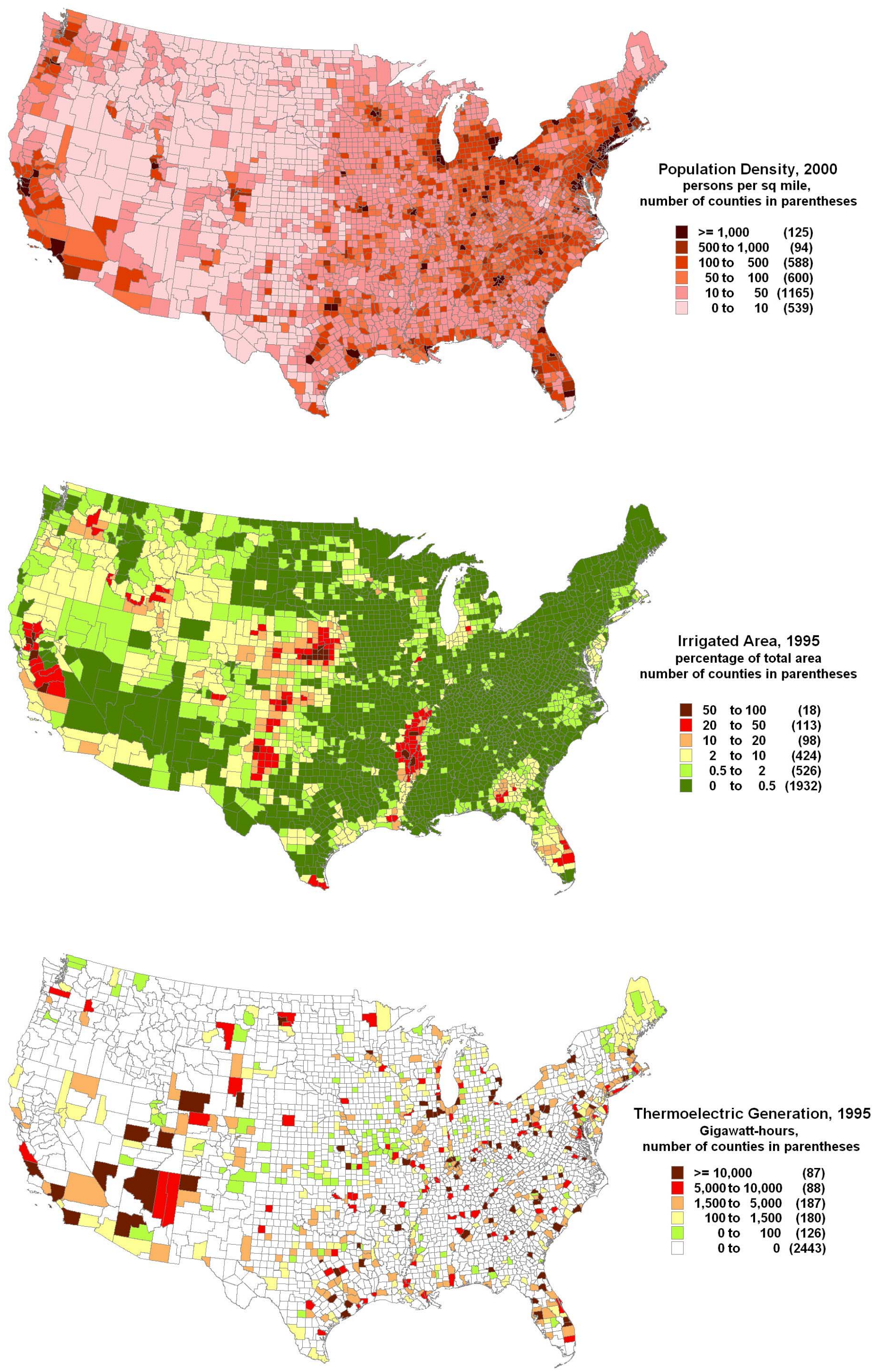


Figure 2-4
(a) Population density for 2000, (b) irrigated area as a percent of total county area in 1995, and (c) thermoelectric generation in 1995 for the US.

Figure 2-5 shows the total withdrawal of freshwater for all uses from surface water and groundwater 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, in the Great Lakes region, eastern Washington, Idaho, and eastern Texas and Louisiana. Although we use 1995 water use data extensively in this report because it is the most recent data, it is important to point out that with respect to precipitation, most areas of the US in 1995 were within 15% of their means for 1934-2002. This is important because the water use data may have been skewed if it had been an unusually wet or an unusually dry year.

Total freshwater withdrawals are plotted as a percentage of available precipitation in Figure 2-6. 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 manmade flow structures. In some cases, they may also be indicative of unsustainable groundwater withdrawal. Areas where this ratio is high are concentrated in the western US, most notably in the southwestern regions.

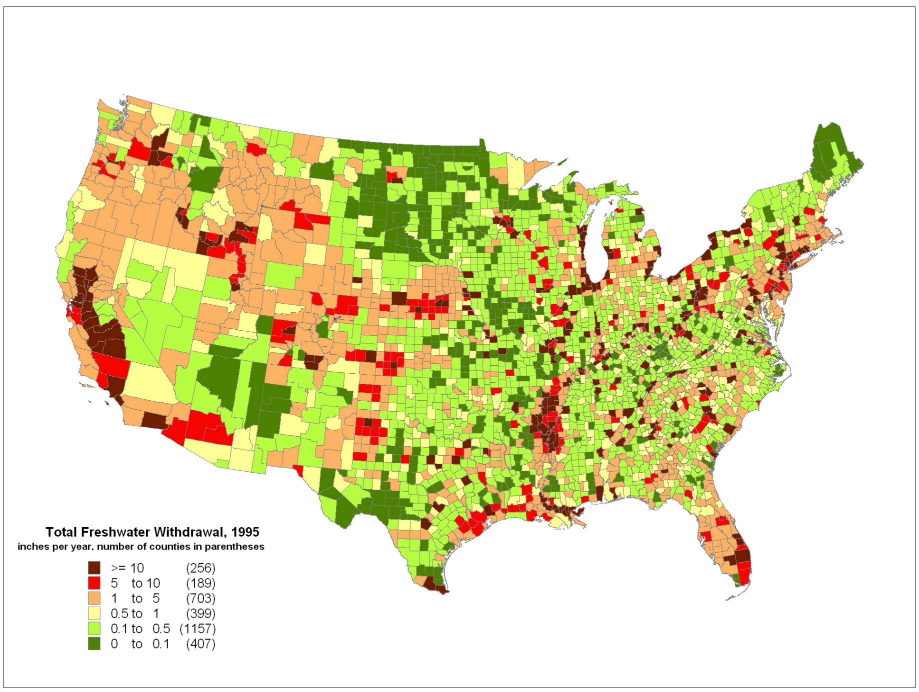


Figure 2-5
Total freshwater withdrawal from surface water and groundwater sources, normalized to inches per year to account for counties of different areas, in 1995 for the US.

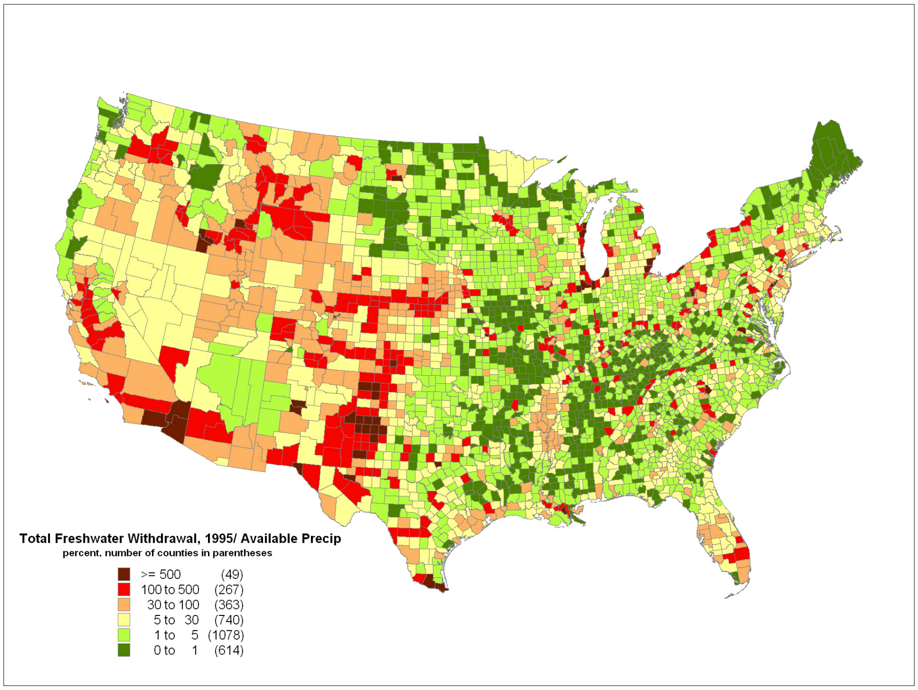


Figure 2-6
Total freshwater withdrawal in 1995 as a percent of available precipitation. Higher values of this ratio are indicative of the extent of water resources development in an area. Values greater than 100, are indicative of imports from other regions.

The ratio of groundwater withdrawal to available precipitation is shown in Figure 2-7. Groundwater 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 during drought years. The available precipitation is the maximum amount of water that can percolate into groundwater in a region (in reality, a substantial fraction will not enter groundwater but will be transported in surface water bodies). When this ratio exceeds 100%, it is an indication that the groundwater withdrawal exceeds local replenishment. In many cases this may be indicative of unsustainable groundwater withdrawal, unless interbasin transfers or recharge occurs. For the US, it appears that this ratio exceeds 100 in parts of northern Texas, Kansas, Nebraska, that overlie the High Plains (Oglalla) Aquifer, a well-known overdraft area (USGS, 1999), and Arizona and southern California. It is also high in southern Florida, Idaho, 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 chapter. Withdrawal data for these two uses are shown in Figure 2-8 (a) and (b) using the same scales and colors. In general, areas of high agricultural withdrawal are in the western US, whereas areas with high thermoelectric cooling withdrawal are in the eastern US. The distribution of agricultural withdrawal is more widely distributed than for thermoelectric withdrawal. Although not shown at the resolution of these maps, locations of withdrawal for thermoelectric cooling are likely to be far more localized within counties than locations of irrigation water withdrawal (NAS, 2002).

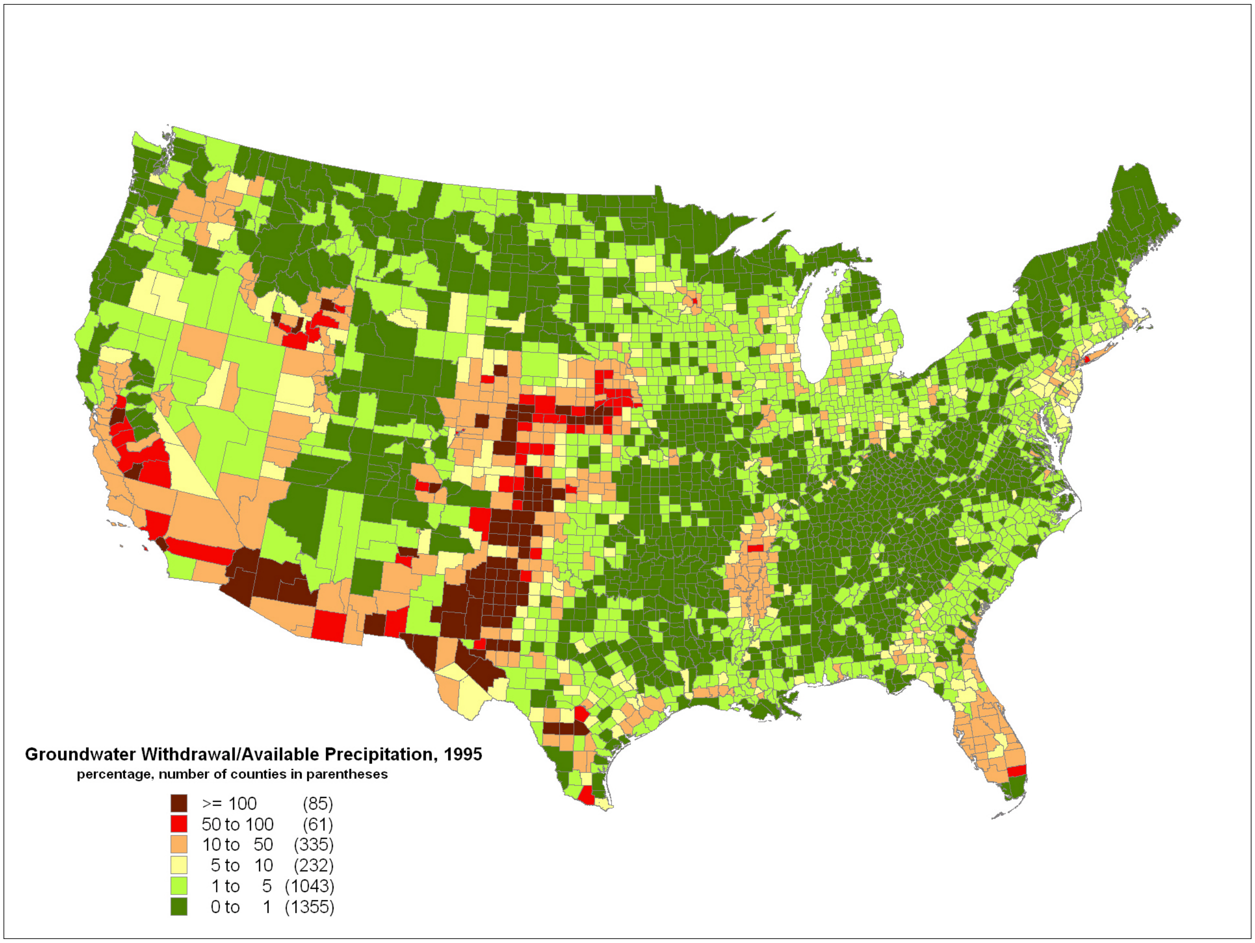
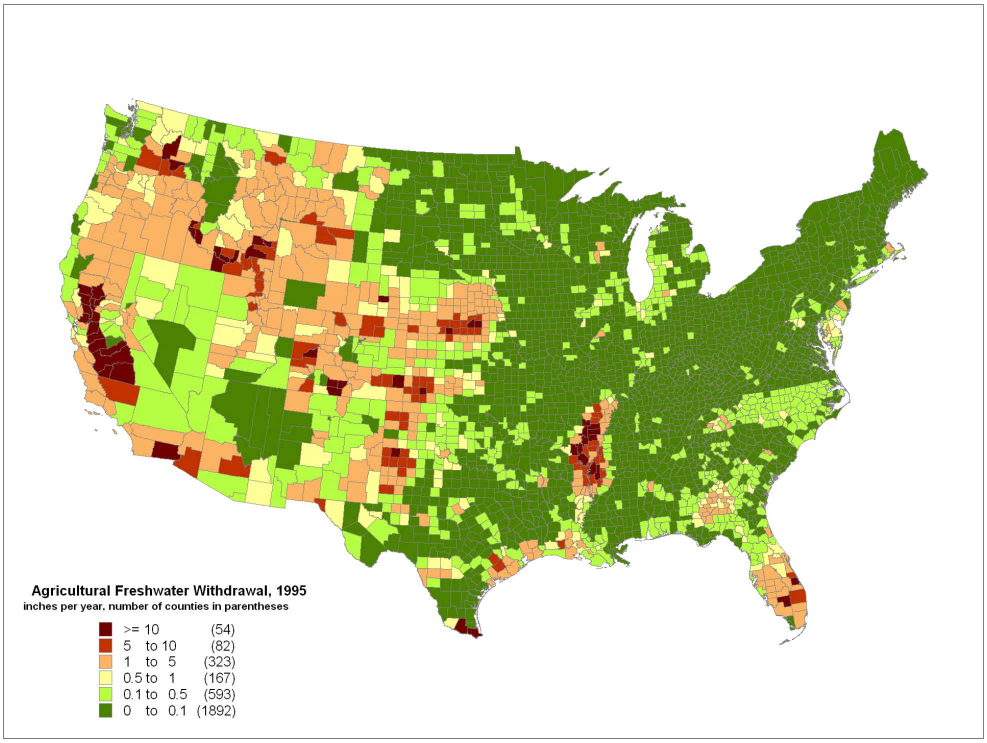


Figure 2-7
Groundwater (fresh) withdrawal in 1995 as a percent of available precipitation. Increasing values of this ratio are indicative of unsustainable groundwater withdrawal, in excess of recharge, or groundwater mining.



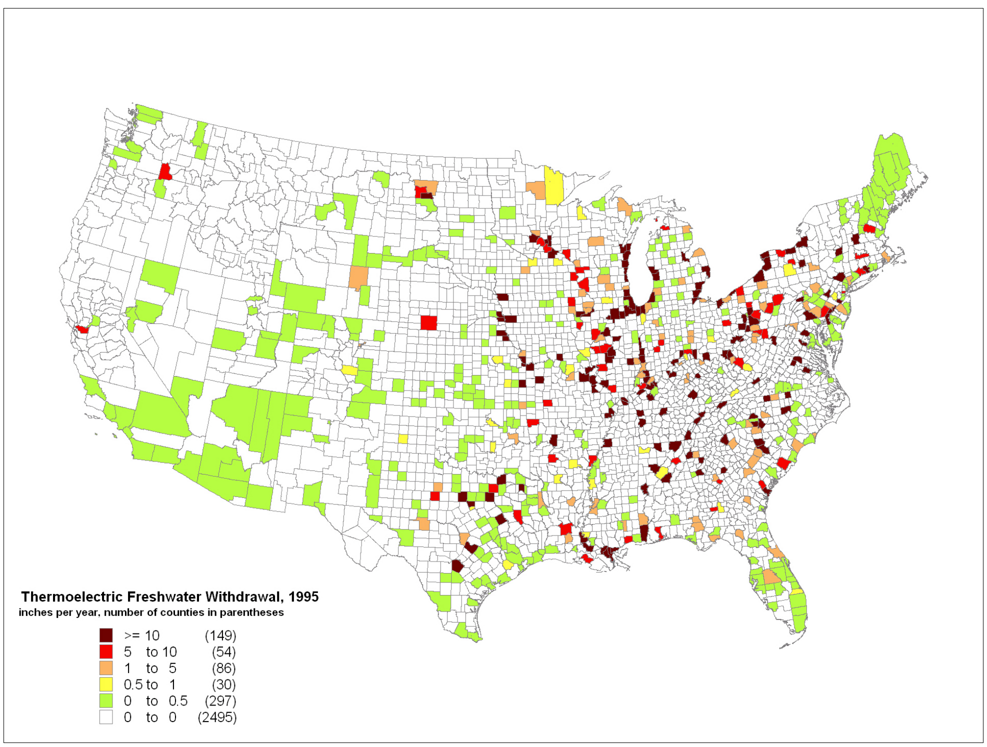


Figure 2-8
Freshwater withdrawal for (a) irrigation and (b) for thermoelectric cooling in 1995, expressed in inches per year to normalize across counties of different areas.

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, and groundwater) across the nation. The development of data in this area is one of the long-term goals of the USGS (USGS, 2002b). For the purpose of this analysis we propose a relatively simple approach to estimating withdrawal of stored freshwater on a national scale. Storage withdrawals are greatest during the warm, dry months of the year, which we assume to be 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 we do not have monthly water use data available, we make the following assumptions to estimate the withdrawal for the summer months from the annual freshwater withdrawal:

(i) we assign irrigation water application during each month of the year in proportion to the difference between precipitation and PET, for months where PET exceeds precipitation, using essentially the same approach as is used in the field,

(ii) we assume thermoelectric cooling withdrawal is proportional to electricity generation, and 28% of the annual total is assumed to occur during the summer months (based on national monthly generation data from the EIA shown in Figure 2-9),

(iii) for domestic use, we assume that half the use is based on a uniform distribution through the year, and half is based on the precipitation-PET difference similar to that used for irrigation; this reflects the variability of outdoor domestic use that varies seasonally, and

(iv) other withdrawals are assumed to be uniform during the year and 25% of the annual withdrawal occurs in 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, defined as available precipitation minus withdrawal in July, August, and September is plotted in Figure 2-10. Many regions of the country, both in the eastern and western US, had substantial summer deficits in 1995 that were met through some form of stored water, such as snowmelt, reservoir or lake storage, and groundwater. 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.

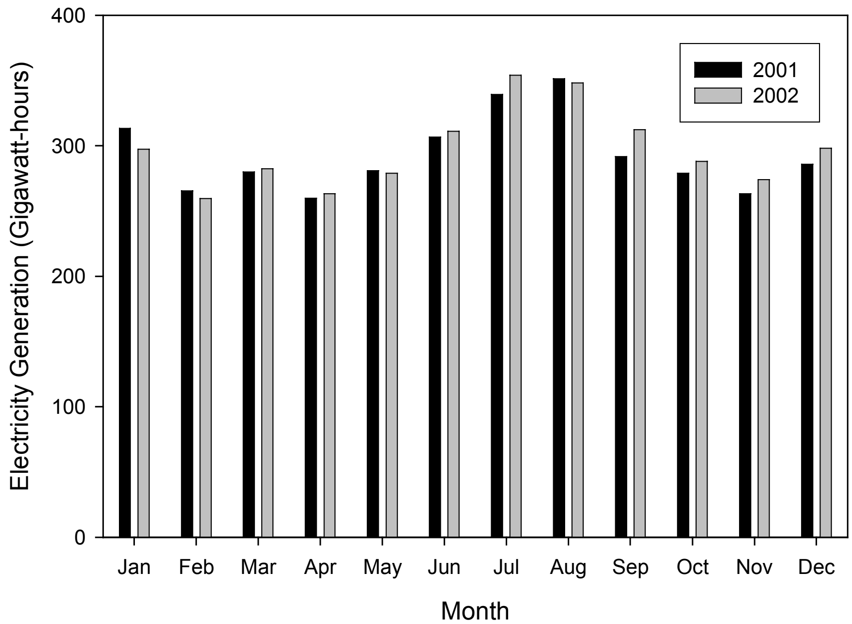


Figure 2-9
Thermoelectric power generation by month for 2001 and 2002 (EIA data). The total power generated during July, August, and September is about 28% of the annual total.

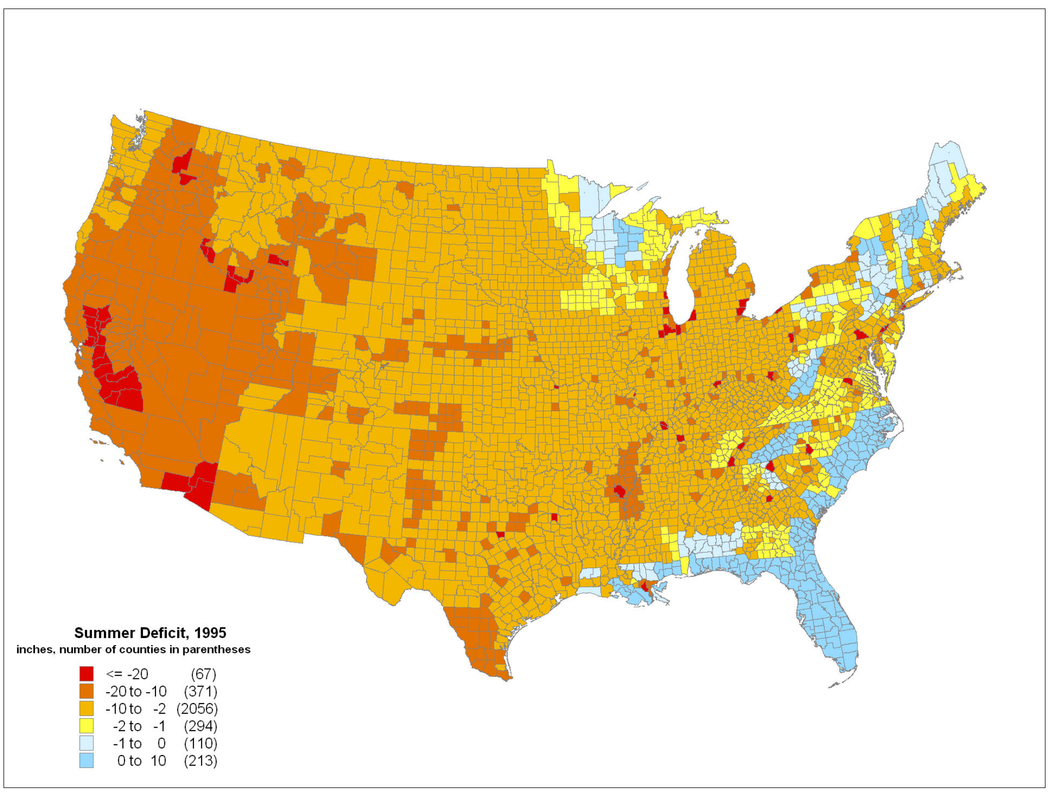


Figure 2-10
Summer deficit for 1995. The summer deficit is calculated as the available water minus the withdrawals, both expressed in inches. Available water is assumed to be represented by the difference between precipitation and evapotranspiration. Withdrawals during the three months of summer are estimated using the approach described in the text.

One may also look at the summer deficit for withdrawals at 1995 levels during years when the precipitation is much lower than in 1995. This is shown in Figure 2-11 where the summer deficit is calculated for precipitation corresponding to the lowest calculated 3-year rolling average value over 1934-2002 for each climate division. As expected, the areas of significant summer deficit are now much larger and are more widespread in the eastern US. Figure 2-11 shows that if a dry year, such as that represented by the lowest 3-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 US, and not limited to what are thought to be dry areas.

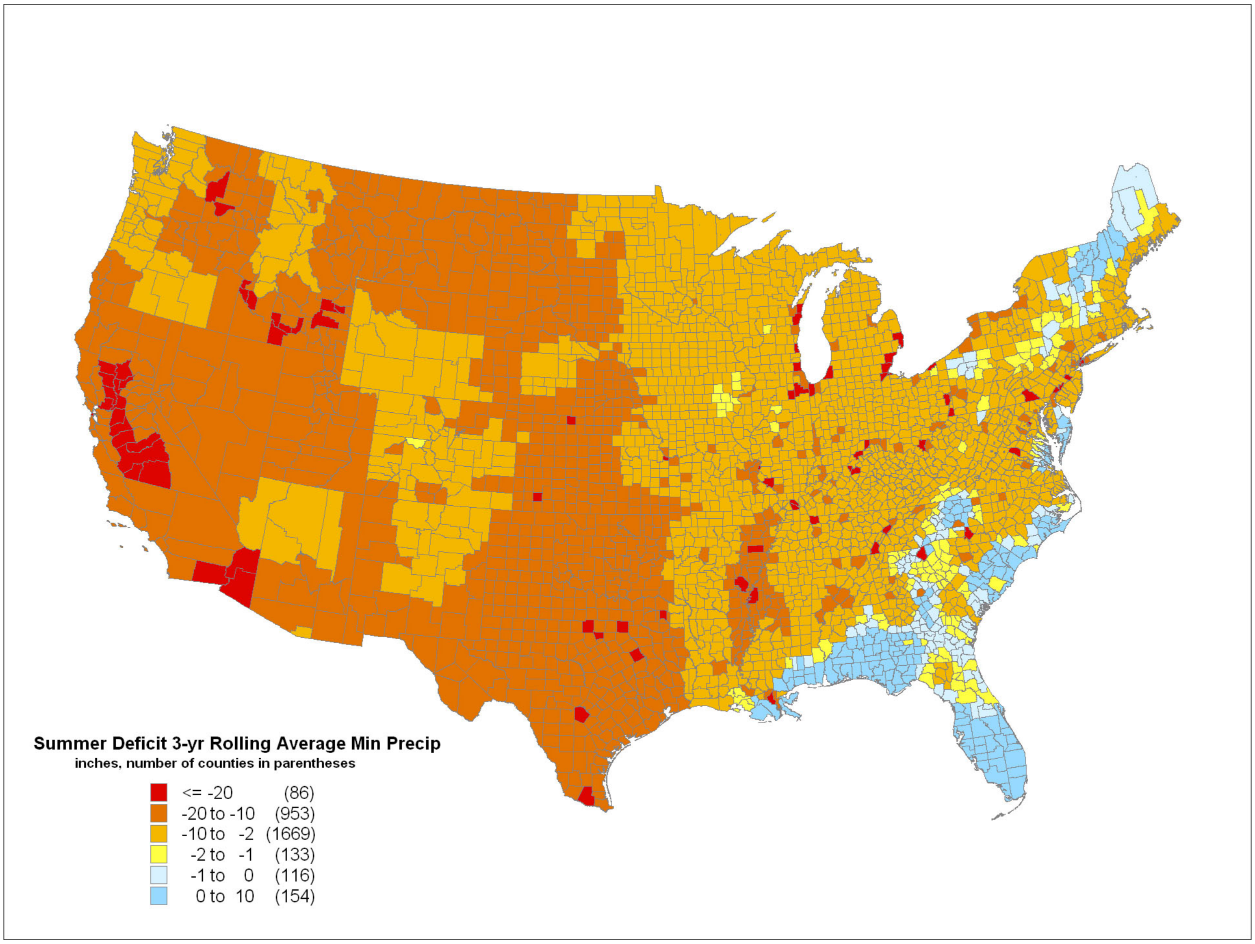


Figure 2-11
Summer deficit for 1995 withdrawals, but using the lowest three-year rolling average precipitation over 1934-2002. The rolling average minimum was calculated for each climate division, and may have occurred in different years in different climate divisions.

Overall, the USGS data permit us to paint a fairly well-resolved picture of water use across the US in 1995. To a certain extent, these data are sufficient to identify regions where water supply shortages may occur. However, there are two limitations to depending solely on these data to draw conclusions on future water sustainability. First, looking to the future, 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. We address these issues in two chapters that follow. In Chapter 3, we use the data on trends of population and power generation as a basis for making projections of future water requirements at a national scale at the spatial resolution of counties. In Chapter 5, we discuss and apply a framework for estimating the water budget at a smaller scale to identify water sustainability features that are not always apparent in a national-scale review.

3
PROJECTIONS OF WATER DEMAND FOR 2025

Assessment of municipal or urban water demand is a mature area of study, and is generally well characterized (US Army Corps of Engineers, 1998; Planning and Management Consultants, 2001). Overall freshwater demand, which consists of municipal and other uses such as industrial, power generation, irrigation, etc., is considerably more difficult to predict. Overall water demand for the US as a whole has been projected in many studies before, but not always very accurately (Lins and Stakhiv, 1998). In the early part of this century, freshwater use was generally well correlated with population. However, in the last two decades, this relationship does not appear to have held. This is illustrated in Figure 3-1, which shows the decline in freshwater withdrawals since 1985 even as the total population increased by 10%. 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 1968-1975 cited in Lins and Stakhiv, 1998 and Guldin, 1989) 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 even a state because most water is not used directly, but indirectly in electricity generation, agriculture, and 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 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) to 307 bgd. The actual withdrawals estimated by USGS for 1995 were 342 bgd (USGS, 1998). 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. It is useful to compare the WRC withdrawal estimates for 1975, the USGS estimates for 1975 and 1995, and the WRC forecasts for 2000, as shown in Table 3-1. The USGS does not generally make projections of future withdrawals, and 1995 is the most recent year for which these estimates are available. Table 3-1 shows that although the total withdrawals estimated by the WRC and USGS studies are 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%. Resolution of the substantial difference in the estimated water withdrawal for thermoelectric cooling for 1975 is beyond the scope of this study. 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 1995. 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 (USGS, 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). Unfortunately, 1978 was the last year in which the federal government conducted a national-scale assessment of water supply sustainability (GAO, 2003).

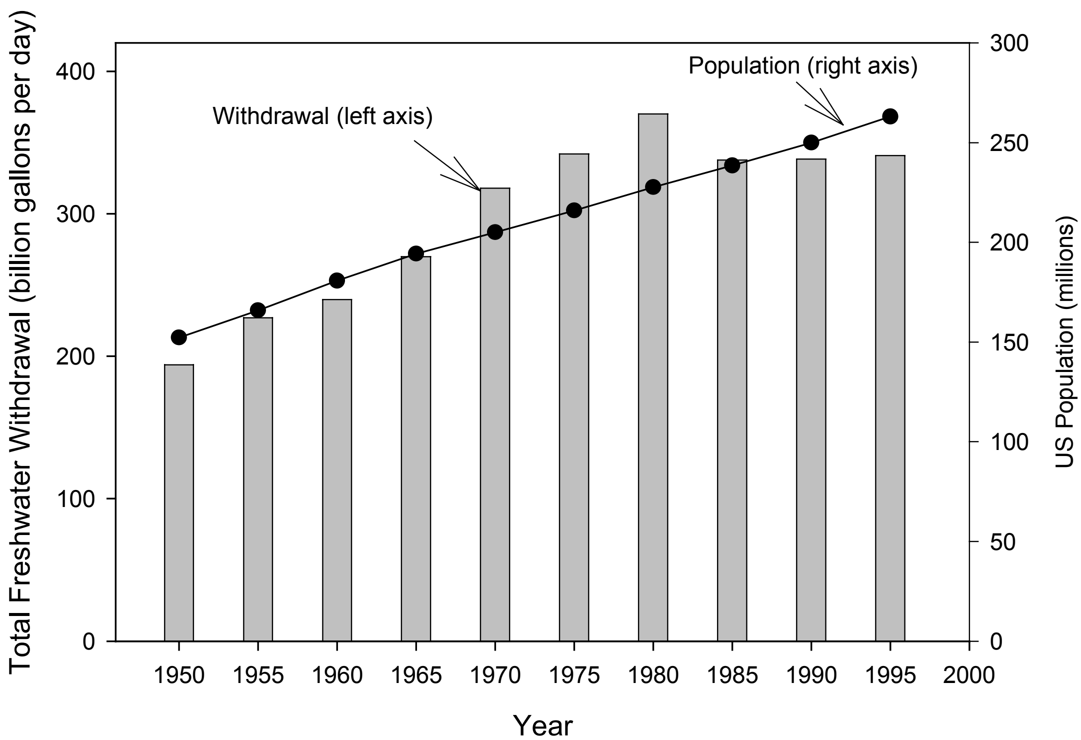


Figure 3-1
Total freshwater withdrawal (gray bars, left axis) and population (line, right axis) in the United States. Water withdrawal data from the USGS surveys between 1955 and 1995, population data from the statistical abstract of the United States.

Table 3-1
Total Freshwater Withdrawal (billion gallons per day) for Different Sectors of the Economy as Estimated and Projected by the Water Resources Council and USGS

Use Category	WRC, 1975	2000 Projected by WRC	USGS, 1975	USGS, 1995
Domestic Municipal	21.2	29.9	20.0	22.7
Domestic Rural	2.1	2.4	2.8	3.4
Commercial	5.5	6.7	NR	9.6
Manufacturing	51.2	19.7	NR	27.1
Commercial + Manufacturing	56.7	26.4	47.1	36.7
Irrigation	158.7	153.8	140.0	133.7
Livestock	1.9	2.6	2.1	5.5
Thermoelectric	88.9	80.1	130.0	131.8
Other	8.9	13.8		8.5
Total	338.0	307.0	342.0	342.3

Over the period 1975-1995 for which we have water withdrawal data, substantial changes in the factors that influence water use have occurred: the total population of the US increased from 216 million to 263 million, the gross domestic product increased from $3.8 trillion to $6.9 trillion (in 1992 dollars), the electricity production by utilities increased from 1,917 to 2,994 thousand gigawatt-hours, and farm acreage decreased from 1,059 million acres to 963 million acres. Despite changes that would generally suggest increases in water withdrawal over 1975-1995, particularly population and electricity production, withdrawals have remained essentially uniform, thus indicating the greatly improved water use efficiency in many sectors of the economy.

We use a combination of data from 1975 and 1995 to project water requirements in the future. To begin with, we assume that potential increases in requirements of water are largely controlled by changing demand due to population and electricity production increases. Other uses of water, such as irrigation, 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:

(i) we may assume that rates of use (such as per capita withdrawal for domestic use, and water used per megawatt hour of electricity generation) remain at their current levels, even as the total population or total electricity generation increases (the “business as usual scenario”); or,

(ii) we may assume that the rates of water use also 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, one or the other scenario may be more accurate. The business as usual scenario is appropriate if we think that the improvements in efficiency have reached a maximum, and that further reductions in the rate of water use may not be possible. The improved efficiency scenario supposes that we can continue with decreasing rates of water use in key sectors of the economy. Evaluation of both scenarios together provides an upper and lower estimate of regional water requirements. Our goal is to assess the changes in water requirements at the scale and resolution that we have used in Chapter 2, i.e., at the county level across the continental US.

The projected growth of population for the United States as a whole is shown in Figure 3-2. The medium to high rate of population growth suggests that the US population will grow by more than 20-40% over the next 25 years. Interestingly, from the perspective of water sustainability, a significant fraction of the population growth in the last decade has occurred in relatively dry regions of the country. This is shown in Figure 3-3, which plots the population density across the US and the change in population between 1990 and 2000 using county level data from the Census Bureau. To evaluate domestic water demand in 2025, we estimate that the population in each county will exhibit the same decadal rate of growth that it did over 1990-2000. The population thus forecast for 2025 is shown in Figure 3-4. 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 increase in population.

The forecast growth of electricity generation over 2000-2025 from the Energy Information Administration reported at the census division level is shown in Figure 3-5. Each census division comprises several states (EIA, 2003). 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, we made four assumptions: (i) we applied the actual change from 1995-2000, reported at the state level to all counties within a state that had any form of power generation (hydroelectric or thermal), (ii) we then applied the forecast percent increase in generation from 2000-2025 to all counties within a census division that had any form of power generation (hydroelectric or thermal), (iii) counties that have no generation at present, were not allocated any new generation, and (iv) 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 can be thought of as conservative from the water requirement standpoint. A map with the projected 2025 thermoelectric generation is shown in Figure 3-6, and may be compared with 1995 generation shown in Figure 2-4(c). Areas with significant thermoelectric power generation are in the mid-west, the southeast, and the southwestern states.

To calculate the water requirements for the business as usual scenario in 2025, we assumed that the irrigation, livestock, mining, industrial, and commercial water withdrawals were unchanged from their 1995 values. New domestic demand was calculated by multiplying the projected 2025 population (shown in Figure 3-4) 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 (i.e., gallons withdrawn per megawatt-hour of electricity production, shown in Figure 3-7). If a county did not have any thermoelectric generation in 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 3-8. 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 harder to meet than a similar increase in a region with greater water availability.

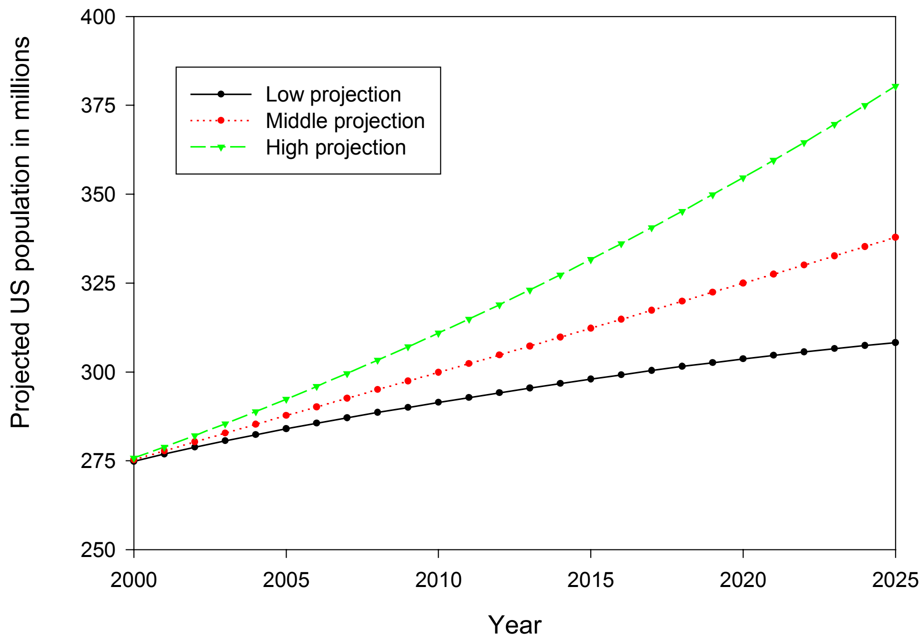


Figure 3-2
Projected total population of the United States as a whole from the US Census Bureau for different assumptions in growth rate (low, medium, and high).

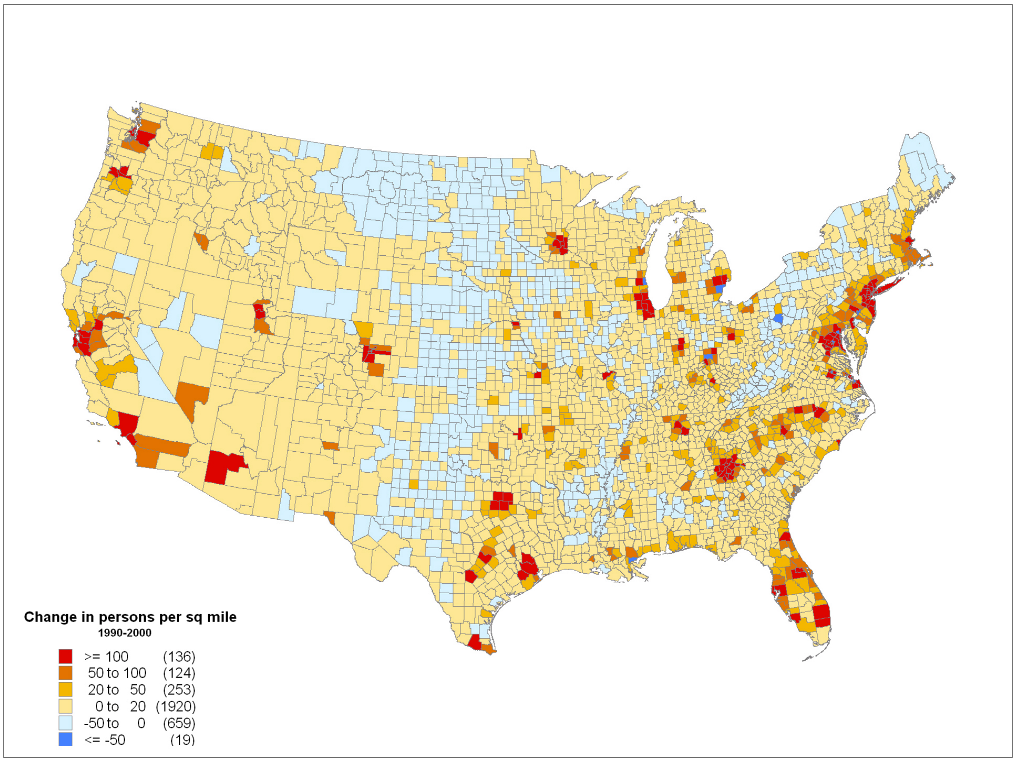


Figure 3-3
Change in population (persons per square mile) from 1990 to 2000 across the US.

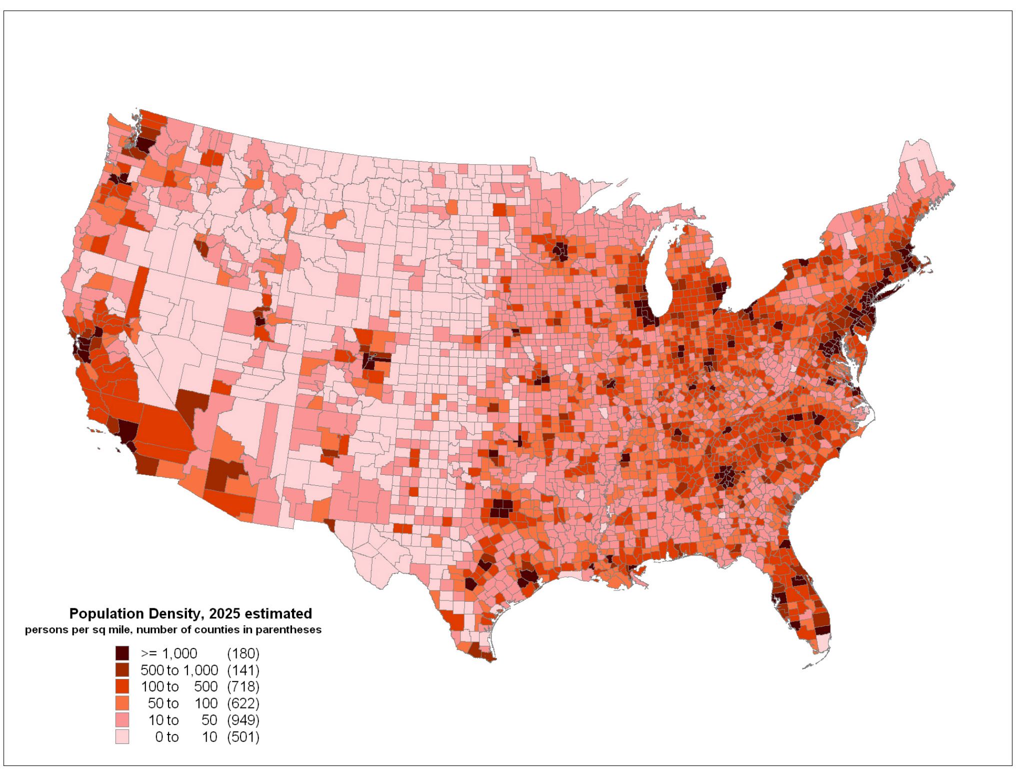


Figure 3-4
Projected population density of the United States for 2025.

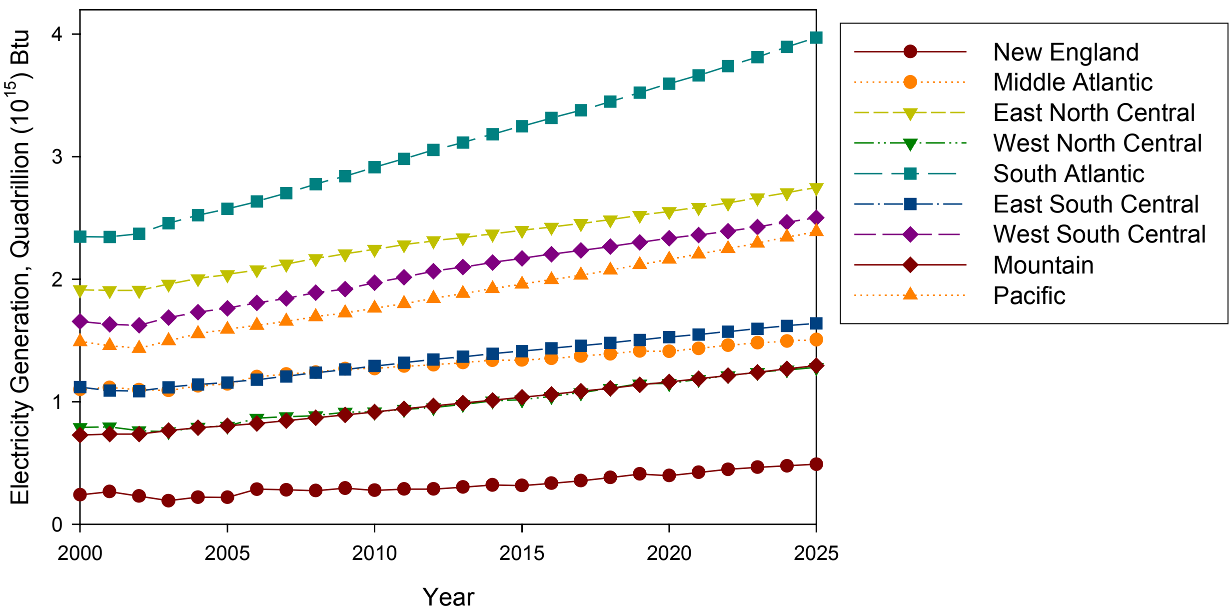


Figure 3-5
Energy demand for different census divisions of the US, projected by the Energy Information Administration, Department of Energy (1 quadrillion Btu = 2.398x10^5 gigawatt-hours).

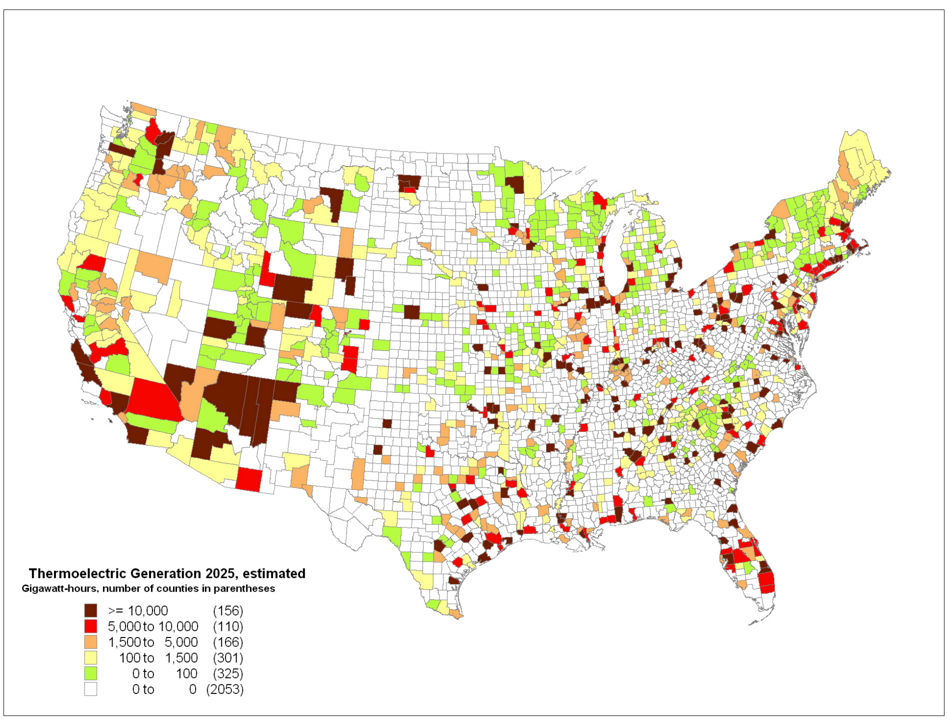


Figure 3-6
Projected thermoelectric generation for 2025 for the US, based on the Energy Information Administration forecasts shown in Figure 3-5.

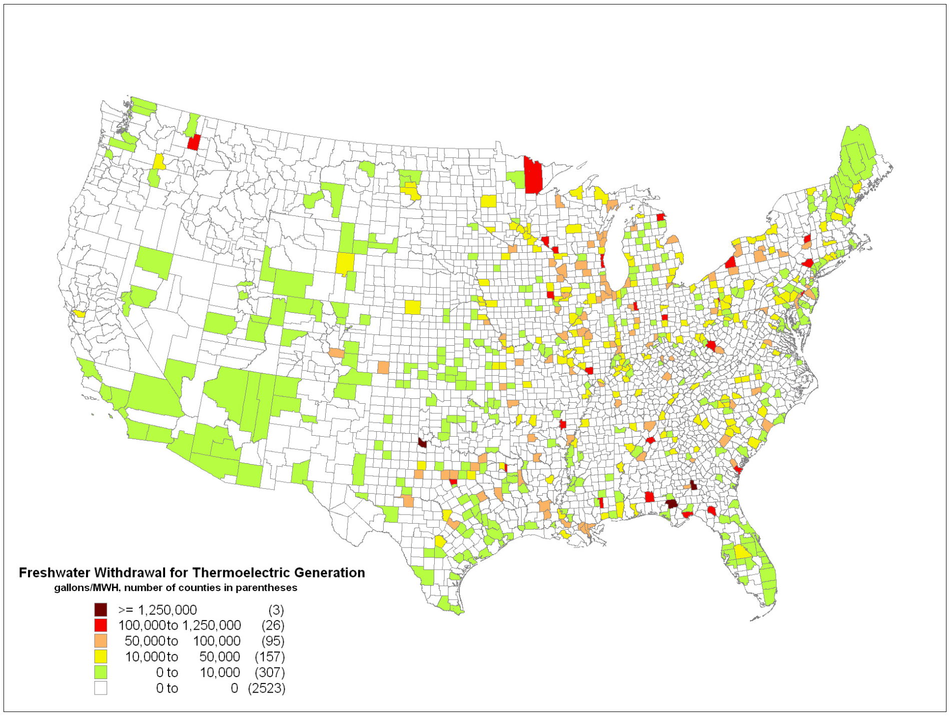


Figure 3-7
Rate of cooling water use (gallons per megawatt hour generated) by thermoelectric power plants across the US.

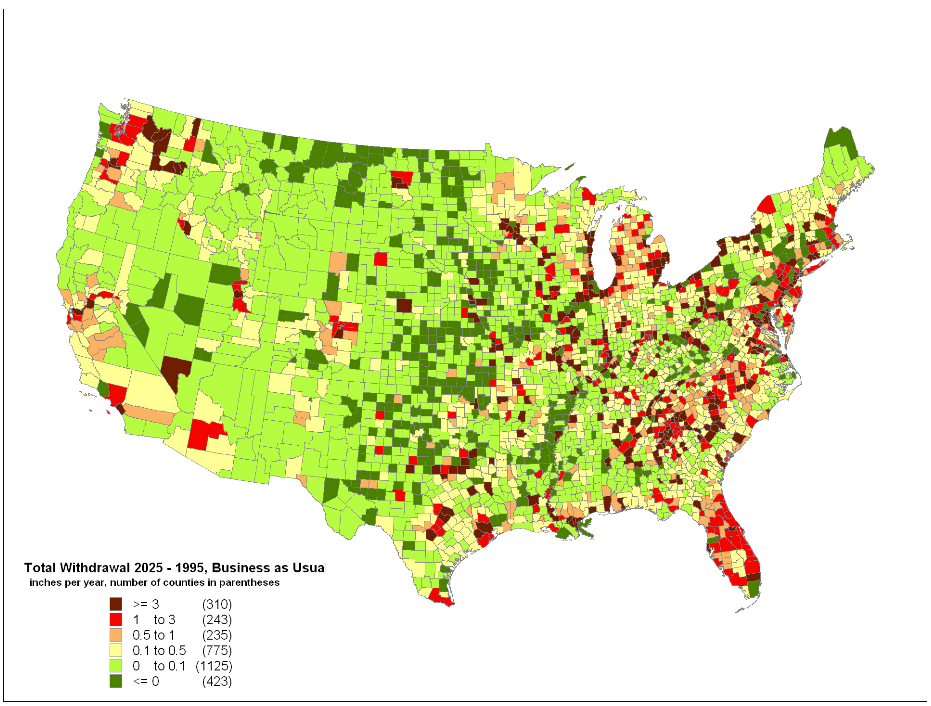


Figure 3-8
Change in water withdrawal requirements from 1995 to 2025, in inches per year, for the business-as-usual scenario.

To calculate the water requirements for the increased efficiency scenario, we assume that the trends in rates of water withdrawal for domestic consumption and for thermoelectric cooling follow the same annual rates of change over 1995-2025 that they have exhibited over 1975-1995. In general we expect an increase in the efficiency of freshwater use in thermoelectric generation because of improvements in cooling technologies. For example, EPRI (2002b) provides an overview of various dry-cooling and wet-dry hybrid cooling systems that can substantially reduce cooling water requirements. These are associated with higher capital costs and reduced efficiency of power generation, but may be practical in areas of severe water scarcity. Freshwater use efficiency may also improve due to a substitution of freshwater by saline water (from seawater or from groundwater) and by reclaimed wastewater, both of which are becoming more common in recent years. Consistent databases for thermoelectric generation and domestic water use are only available at the USGS Water Resources Region (WRR) level from the Water Resources Council Study of 1978. Hence, the annual percent change in rate of water use over 1975-1995 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 shown for 1975 and 1995 in Tables 3-2 and 3-3. Also calculated is the annual percent decrease in the rate of use at the WRR level. Total water requirements in 2025 for the increased efficiency scenario were calculated by using 1995 withdrawals for irrigation, livestock, mining, industrial, and commercial use, and using 2025 estimated population and 2025 per capita domestic use, and 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% annual *increase* in freshwater use from 1975 to 1995. This is an anomalous result, and, if based on valid data, may be explained by a possible shift in power generation from coastal areas using seawater to more inland areas using freshwater for cooling. Data at a sufficiently detailed spatial scale for 1975 are difficult to obtain and a further explanation of this anomaly was beyond the scope of this study. For this region it was assumed that the rate of cooling water use would not change from 1995-2025, but remain at 1995 levels. A map of the change in water withdrawal requirements from 1995 for the increased efficiency scenario is shown in Figure 3-9. This map is drawn using the same colors and scales as used in the map for the business-as-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, DC, New York, Atlanta, Miami, Houston, San Antonio, Dallas, Phoenix, Las Vegas, and eastern Washington.

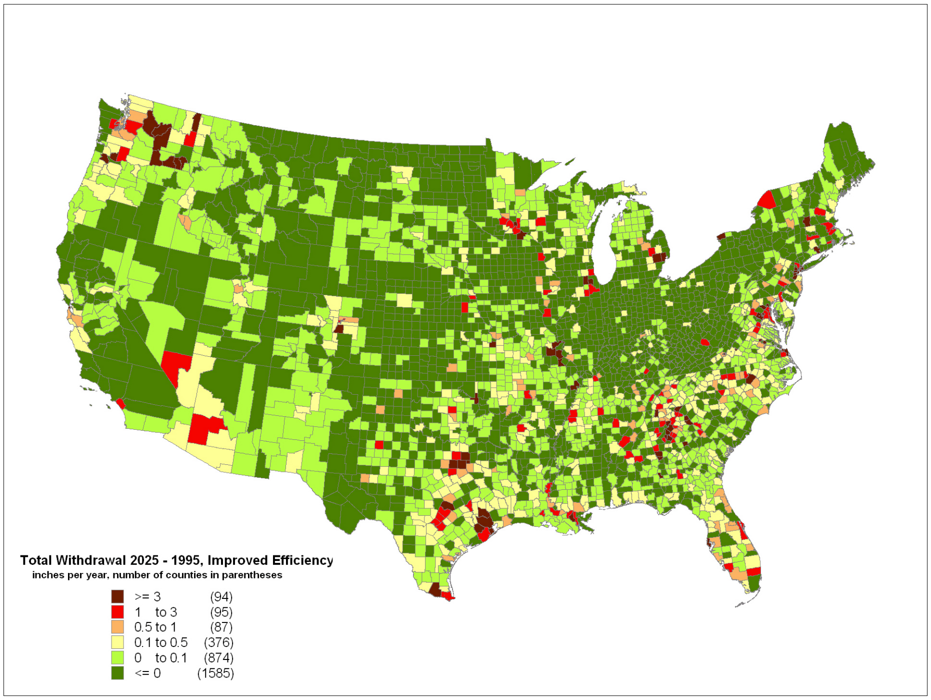


Figure 3-9
Change in water withdrawal requirements from 1995 to 2025, in inches per year, for the improved-efficiency scenario.

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/products, it is not straightforward 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 1975-1995, with different regions showing increases and decreases in water use per irrigated acre of land (Table 3-4). Commercial and industrial use are relatively small components of the total withdrawals. Hence assuming that changes in water requirements for these latter uses will not drive the water demand in the coming decades is a reasonable assumption. This is not to say, however, that these withdrawals will remain constant. As pointed out earlier, our 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.

Table 3-2
Change in Thermoelectric Cooling Freshwater Withdrawal 1975-1995

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	64437	1900	84578	1670	29	20	2.0	10.8
2	Middle Atlantic	195067	14000	258586	12664	72	49	1.9	27.6
3	South Atlantic Gulf	220101	18000	504529	19703	82	39	3.6	12.9
4	Great Lakes	182992	25000	218588	22787	137	104	1.3	69.5
5	Ohio	299003	27000	451333	22622	90	50	2.9	20.7
6	Tennessee	48763	8700	50040	4910	178	98	2.9	40.0
7	Upper Mississippi	112704	13000	211119	19070	115	90	1.2	62.6
8	Lower Mississippi	53363	6000	78133	6736	112	86	1.3	57.9
9	Souris-Red-Rainy	956	190	396	38	199	97	3.5	33.0
10	Missouri	55851	4200	167181	8807	75	53	1.8	30.9
11	Arkansas-White-Red	65755	2800	143014	4203	43	29	1.8	16.8
12	Texas-Gulf	122873	7600	224055	7696	62	34	2.9	14.2
13	Rio-Grande	10638	28	7779	18	3	2	0.6	1.9
14	Upper Colorado	22545	160	77202	127	7	2	7.1	0.2
15	Lower Colorado	23762	150	62360	64	6	1	8.7	0.1
16	Great Basin	3083	83	16291	24	27	1	13.5	0.0
17	Pacific Northwest	9602	36	16961	385	4	23	-9.4	338.1
18	California	84763	1500	76008	211	18	3	8.9	0.2
19	Alaska	1116	21	3770	31	19	8	4.0	2.4
20	Hawaii	5167	170	6366	67	33	11	5.5	1.9
21	Caribbean	9937	0	16534	4	0	0	-	-
	US Total	1592478	130538	2674822	131837				

Table 3-3
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	10000	830	10426	717	83	69	0.9	52
2	Middle Atlantic	34800	3700	35684	3344	106	94	0.6	78
3	South Atlantic Gulf	18000	2000	30774	3146	111	102	0.4	90
4	Great Lakes	18000	1800	16963	1400	100	83	1.0	62
5	Ohio	15400	1600	17990	1138	104	63	2.5	30
6	Tennessee	2370	210	2620	209	89	80	0.5	68
7	Upper Mississippi	16600	2100	17974	1454	127	81	2.2	41
8	Lower Mississippi	5300	590	6328	703	111	111	0.0	111
9	Souris-Red-Rainy	366	41	446	26	112	59	3.1	23
10	Missouri	6760	870	8978	966	129	108	0.9	82
11	Arkansas-White-Red	5900	670	7681	767	114	100	0.6	82
12	Texas-Gulf	8240	930	15690	2158	113	138	-1.0	185
13	Rio-Grande	1470	250	2297	340	170	148	0.7	120
14	Upper Colorado	309	67	547	85	217	154	1.7	93
15	Lower Colorado	2230	420	4925	755	188	153	1.0	112
16	Great Basin	1200	330	2280	417	275	183	2.0	99
17	Pacific Northwest	4810	720	7476	1016	150	136	0.5	118
18	California	19900	3000	30445	3704	151	122	1.1	88
19	Alaska	184	80	381	38	435	99	7.2	11
20	Hawaii	808	150	1122	131	186	117	2.3	58
21	Caribbean	2320	270	3585	173	116	48	4.3	13
	US Total	174967	20628	224609	22685				

Table 3-4
Change in Agricultural Water Withdrawal 1975-1995

HUC-2 Code	Water Resources Region	Acres Irrigated in thousands, 1975	Irrigation Water Withdrawal, mgd, 1975	Acres Irrigated in thousands, 1995	Irrigation Water Withdrawal, mgd, 1995	Irrigation Gallons Per Acre, 1975	Irrigation Gallons Per Acre, 1995	Annual Percent Decrease
1	New England	86	57	103	146	663	1422	-3.9
2	Middle Atlantic	290	230	328	288	793	879	-0.5
3	South Atlantic Gulf	2700	3100	3562	4620	1148	1297	-0.6
4	Great Lakes	180	99	556	315	550	567	-0.1
5	Ohio	73	34	222	104	466	468	0.0
6	Tennessee	24	7.2	34	29	300	863	-5.4
7	Upper Mississippi	340	150	1054	484	441	459	-0.2
8	Lower Mississippi	2700	4900	5728	8131	1815	1420	1.2
9	Souris-Red-Rainy	41	42	168	88	1024	525	3.3
10	Missouri	12000	28000	13514	24604	2333	1821	1.2
11	Arkansas-White-Red	6600	10000	6117	9250	1515	1512	0.0
12	Texas-Gulf	5300	7100	4279	5531	1340	1293	0.2
13	Rio-Grande	2000	4900	1264	6020	2450	4762	-3.4
14	Upper Colorado	1300	3700	1708	7030	2846	4115	-1.9
15	Lower Colorado	1500	7520	1256	6410	5013	5103	-0.1
16	Great Basin	2400	6000	1607	5109	2500	3180	-1.2
17	Pacific Northwest	7500	28000	7030	25744	3733	3662	0.1
18	California	9300	35000	9539	29060	3763	3046	1.1
19	Alaska	0	0	1	1		399	
20	Hawaii	140	950	136	652	6786	4806	1.7
21	Caribbean	66	230	38	107	3485	2814	1.1
	US Total	54540	140019	58243	133723			

Analogous to the summer deficit computed for 1995 (Figure 2-10), we can compute the summer deficit corresponding to the 2025 business as usual withdrawals using average 1934-2002 precipitation values as shown in Figure 3-10 (a). 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 3-10 (b). The map shows that water sustainability concerns are not limited to the western US, and many regions in the eastern US may require new water supplies during the summer months, or modification of existing patterns of use.

The projected future withdrawals in this chapter can be compared with 10-yearly studies performed by the USDA that project 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 ten-yearly intervals, as part of its mandate under the Resources Protection Act (Guldin, 1989). The Water Resources Council, which we used as the basis for evaluating changes in the rate of water use by region, has ceased to exist since 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 to 495 bgd, in 2020 and 2030 respectively, i.e., an increase of 34 to 43% 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 the Water Resources Council (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 region. 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 was 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 US. Total withdrawals for the continental US were projected by Brown to be from 349 to 356 bgd in 2020 and 2030 respectively for the middle range of population growth, 2-4% higher than 1995 levels, and therefore a significant reduction from the Guldin (1989) estimate. 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% growth from 1995 to 2040), withdrawal would be expected to decrease by about 8% from 1995 levels, driven primarily by reductions in thermoelectric withdrawal, with withdrawal for other uses remaining roughly uniform. Alternatively, for the high population growth scenario (74% growth from 1995 to 2040), the total withdrawal would be expected to increase by 25% 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.

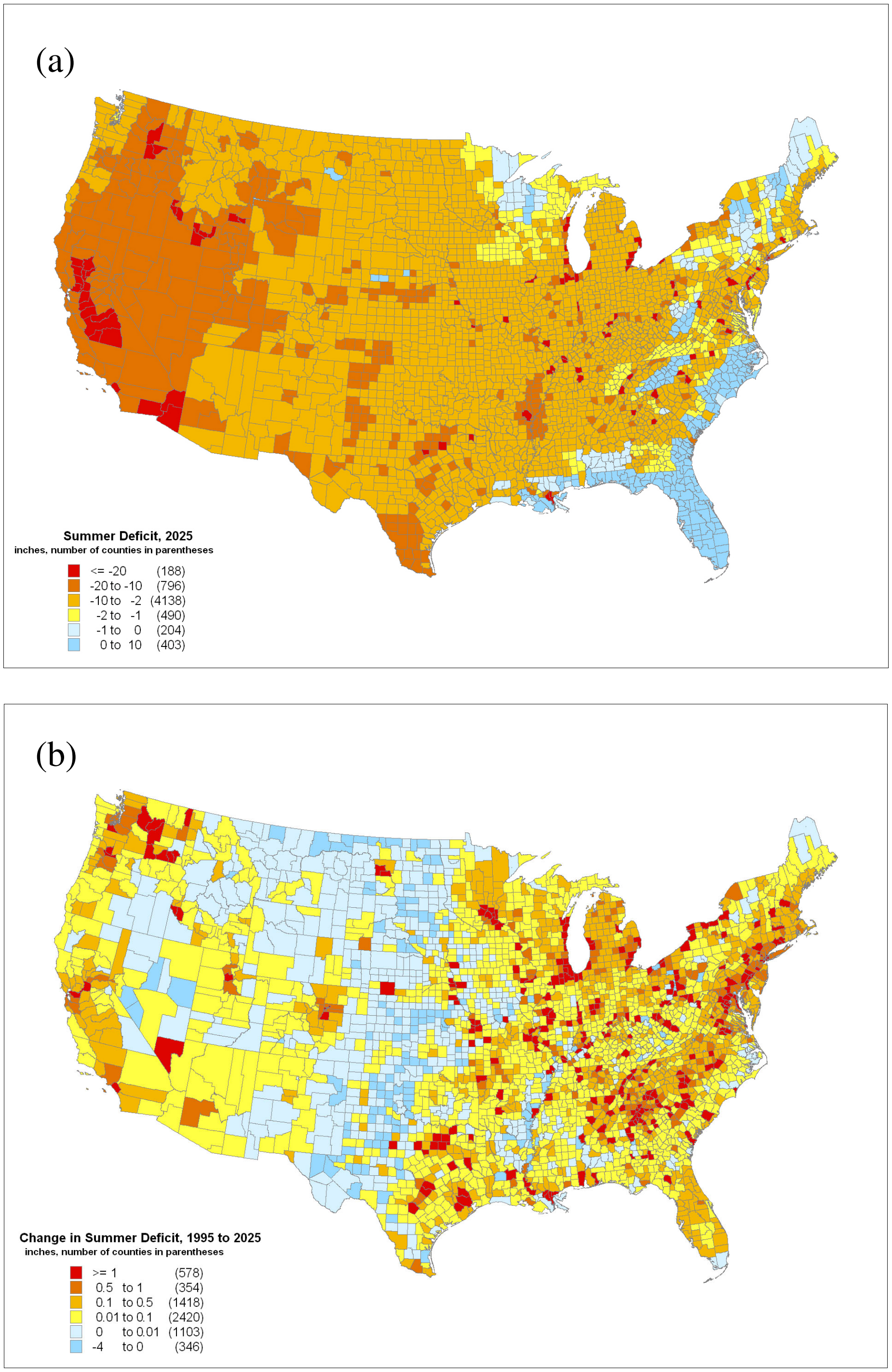


Figure 3-10
(a) Summer deficit in 2025 and (b) the change in summer deficit from 1995 to 2025, in inches per year, for the business-as-usual scenario. Areas with increased summer deficit will need more stored water supplies during the months of July, August, and September.

National estimates projected by the studies above are compared with the estimates produced from this study in Table 3-5. The approach we have used for estimating withdrawal is broadly similar to that used by Guldin (1989) and Brown (1999) except that we have used more region-specific estimates of rates of change of use (at the WRR level rather than the national level), and we assume change to be driven only by domestic and thermoelectric use. On an aggregate national basis, compared to the more recent Brown (1999) projection, our improved efficiency estimate is somewhat lower, whereas the business-as-usual estimate is significantly higher. 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 vs. WRR level) and the incorporation of key hydrologic factors in estimating the extent of water use compared to available precipitation.

Table 3-5
Total Annual Freshwater Withdrawal in the Continental US, in Billion Gallons per Day, from Different Studies.

Year	Study		
	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 highly 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. We calculated these two alternative scenarios using the best currently available information 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 US.

4
COMPOSITE INDICATORS OF WATER SUSTAINABILITY STRESS

In this chapter, our goal is to develop a synthesis of the multiple layers of data presented in previous chapters into two composite metrics that can be used to identify regions of concern from the viewpoint of water sustainability in general and thermoelectric cooling water availability in particular. Maps of these composite metrics provide a rapid snapshot of water sustainability in the US, and regions identified as having water supply concerns are suitable for further evaluation using more detailed data and modeling.

Any assessment of water sustainability must include a representation of environmental regulatory constraints to freshwater withdrawal. The data that we have presented in the preceding two chapters have dealt with constraints caused by limited quantities of water but not the regulatory constraints. Although water withdrawals are limited by several federal and state regulations these cannot be represented in a simple way over the entire country. However, for the purpose of this study, we have chosen to designate a surrogate that represents the regulatory limits to freshwater withdrawals: the number of endangered aquatic species present in each county across the US. This metric is used as part of our composite index and is shown in Figure 4-1. Areas in the southeast and western US have the greatest prevalence of endangered species, and are likely to face withdrawal constraints for this reason.

We propose a Water Supply Sustainability Index that evaluates water supply constraints based on metrics representing six different types of criteria. The criteria and the quantitative metrics used proposed are:

- **Extent of development of available renewable water:** Greater than 25% of available precipitation currently used.
- **Sustainable groundwater use:** Ratio of groundwater withdrawal to available precipitation is greater than 50%.
- **Environmental regulatory limits on freshwater withdrawals:** Two or more endangered aquatic species.
- **Susceptibility to drought:** Summer deficit during low precipitation years is greater than 10 inches.
- **Growth of Water Use:** Business as usual requirements to 2025 increase current freshwater withdrawal by more than 20%.
- **New requirements for storage or withdrawal from storage:** Summer deficit increases more than 1 inch over 1995-2025.

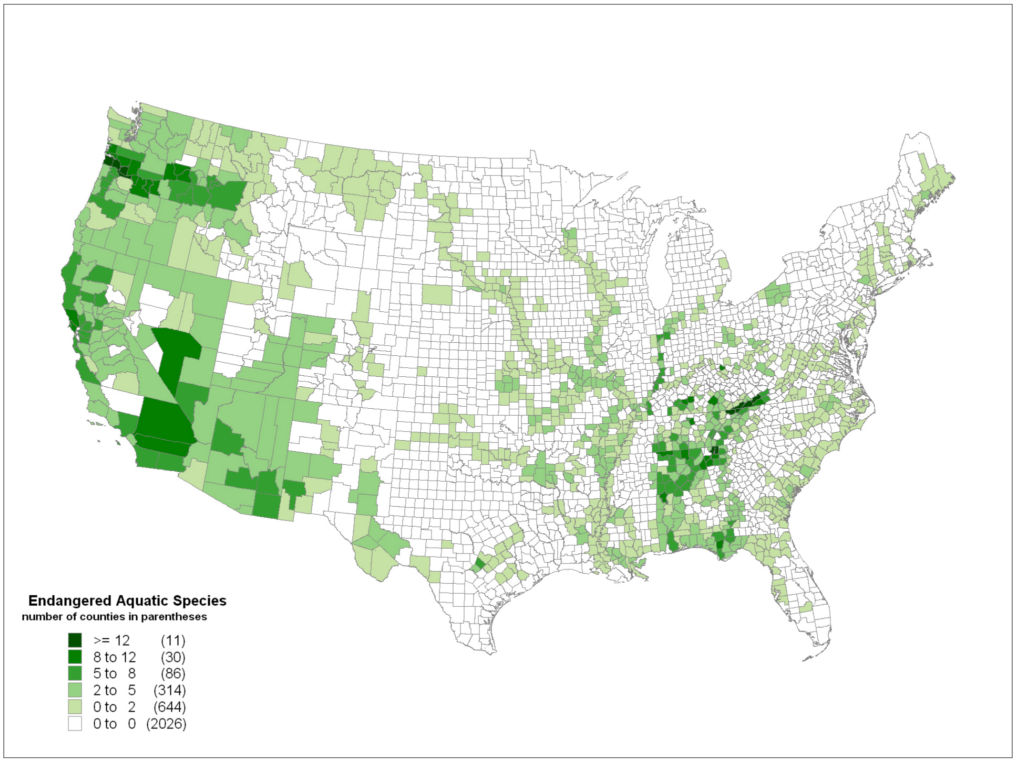


Figure 4-1
Number of endangered aquatic species by county.

If any two of the criteria are met in a county, it is considered to be somewhat susceptible, if 3 of the criteria are met, the county is moderately susceptible, and if 4 or more of the criteria are met, the county is highly susceptible. The Water Supply Sustainability Index is mapped in Figure 4-2. Areas that are susceptible to water supply constraints are concentrated in the southwestern regions of the US, notably California, Nevada, Arizona, and New Mexico. Other regions that are susceptible are located in Washington, Idaho, Texas, Alabama, Georgia, Louisiana, and Florida.

We also propose a Thermoelectric Cooling Water Supply Limitation Index, based on the above, and identify areas as moderately constrained if the Water Supply Sustainability Index score is 2 and the 2025 electricity generation is anticipated to increase by more than 50%, as highly constrained if the Water Supply Sustainability Index score is 3 or more, and the 2025 electricity generation is forecast to increase by more than 50%. The Thermoelectric Cooling Water Supply Limitation Index is mapped in Figure 4-3. Areas where the cooling water supply is likely to be limited occur in all of the Pacific Coast states, Arizona, Utah, Texas, Louisiana, Georgia, Alabama, and Florida.

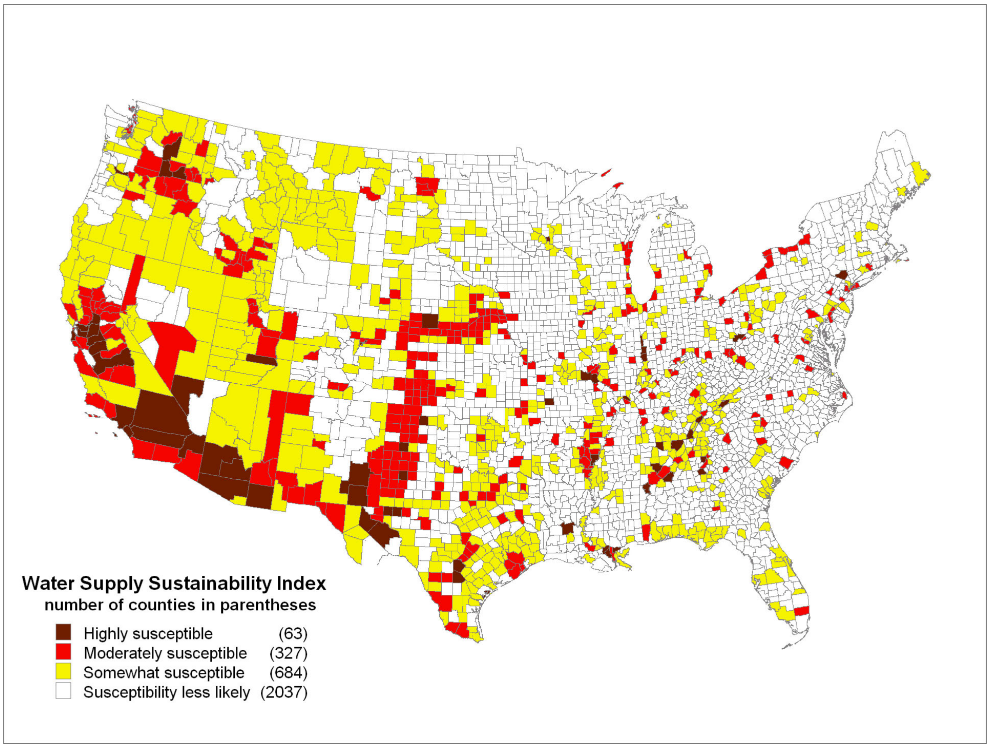


Figure 4-2
Water supply sustainability index.

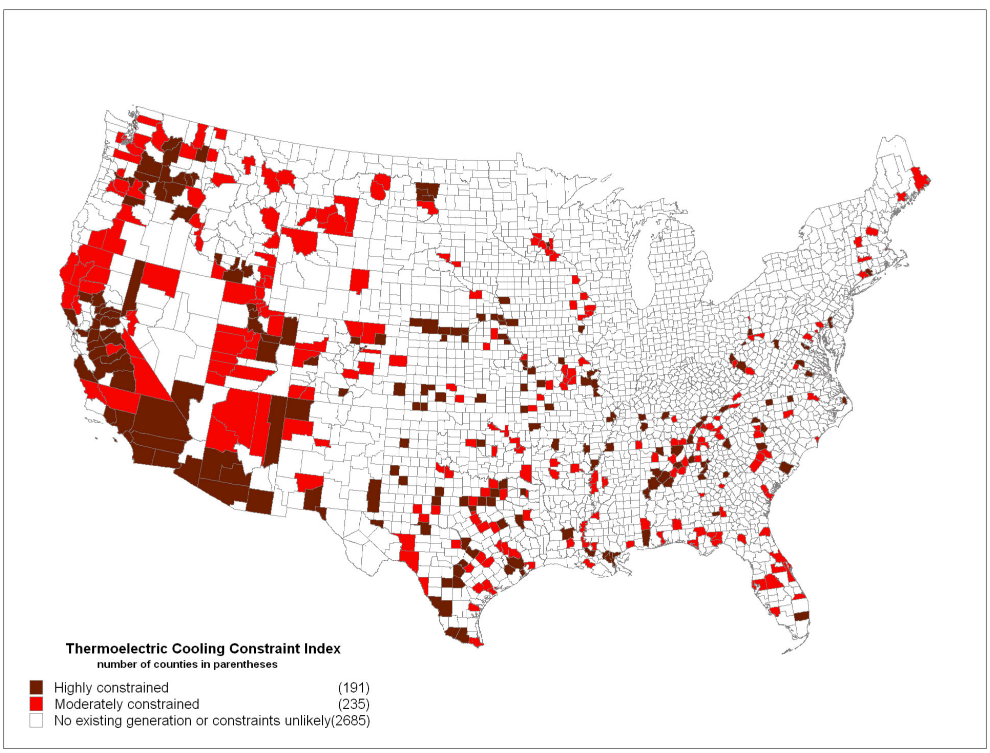


Figure 4-3
Thermoelectric cooling constraint index.

The composite indices presented in this work can be compared with two recent large-scale assessments of water sustainability (Hurd et al., 1999 and USDOI, 2003). The Hurd et al. study was conducted at the 4-digit HUC watershed level (continental US divided into 120 watersheds). Using a mix of data such as level of water resources development, natural variability in streamflow, fraction of precipitation lost to evapotranspiration, groundwater depletion, consumptive use of water in the industrial sector, and an integer index representing institutional flexibility, Hurd et al. identified several regions in the western US (California, Nevada, Arizona, Utah, Colorado, New Mexico, Kansas and Texas) as having water supply constraints. However, this study did not consider trends in future growth of population and electricity generation. Furthermore, the county-level data that we have presented provides a more spatially detailed view of water supply constraints. In particular, the relatively high demands caused by metropolitan areas show up clearly in the county-level maps but not at the 4-digit HUC watershed level in the Hurd et al. study. The DOI (2003) study identified areas in the western US that were ranked according to their potential for water supply conflicts. Several of the areas identified in that study were identified by us as having water supply constraints in Figure 4-2, such as southern Arizona, eastern Washington, California's Central Valley, etc. However, the DOI study did not provide any quantitative information on how these areas were identified, and also did not identify the water supply limitations from the specific perspective of thermoelectric cooling.

In 2002 the US Congress directed the USGS to "prepare a report describing the scope and magnitude of the efforts needed to provide periodic assessments of the status and trends in the availability and use of freshwater resources." In response the USGS proposed to "develop and report on indicators of the status and trends in storage volumes, flow rates, and uses of water nationwide" (USGS, 2002b). Although not all data needed for the proposed assessment are currently available, the indices described in this chapter, based on an incorporation of climatic, demographic, and economic factors along with water use data, may be considered as a step toward a composite indicator of the status of water availability in the US.

5
CASE STUDY: WATER SUPPLY AND DEMAND IN THE PHOENIX, ARIZONA AREA

Water supply and demands are assessed for a specific region that has been identified in Chapter 3 as having significant water sustainability concerns, the Phoenix metropolitan area in Arizona. An assessment at this scale permits consideration of seasonal variability in water supply, evaluation of storage requirements, and finally, consideration of the local, legal, and institutional infrastructure that pertains to water withdrawals. Phoenix is especially relevant for this study because it is one of the fastest growing areas in the nation and has minimal precipitation input (8" annual average precipitation, and 1.4" available precipitation, as defined in Chapter 2, and shown in Figure 5-1). Over much of the 20^{th} century, as the region has grown, groundwater has been one of the major sources of water. This groundwater withdrawal has largely been unsustainable, i.e., withdrawal significantly exceeds recharge, and in many places near Phoenix the water table has dropped by as much as 400 feet over 1900-1998. In recent years, one of the major goals of water resources policy in Arizona has been to ensure that groundwater resources are sustainably used, and that withdrawals do not exceed recharge, both natural and artificial (Groundwater Management Code of 1980, ADWR, 2000c). The principal management goal of the Groundwater Code is for sustainable groundwater withdrawals by the year 2025. Selected areas in the state, where the overdraft is severe, have been identified for intensive groundwater management, and the Phoenix Active Management Area (AMA) is one of them. The boundaries of the AMA are dictated by the underlying aquifers, rather than the watersheds of rivers or other political boundaries. The Phoenix AMA covers 5,646 mi^2 and includes much of Maricopa county, in which Phoenix lies, and also parts of Yavapai and Pinal counties (Figure 5-2). Roughly 10% of the Phoenix AMA consists of Indian lands. To address the issue of unsustainable groundwater use, the state of Arizona requires AMAs to adopt decade-long management plans to improve the efficiency of water use. The most recent management plan for the Phoenix AMA (ADWR, 1999), spans the Third Management Period (2000-2010) and served as an important source of data presented in this chapter.

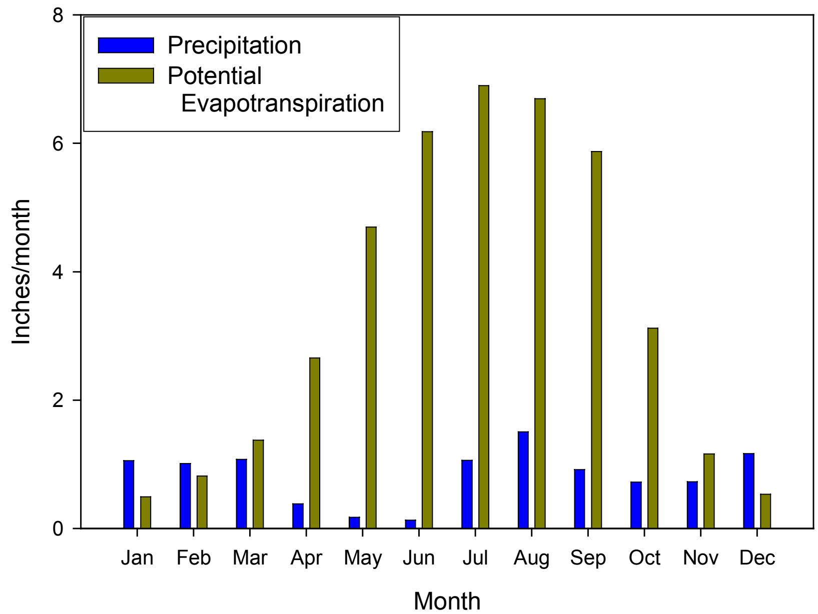


Figure 5-1
Precipitation and potential evapotranspiration in climate division 14, which includes Phoenix. Data are averages of values for 1934-2002, obtained from NOAA.

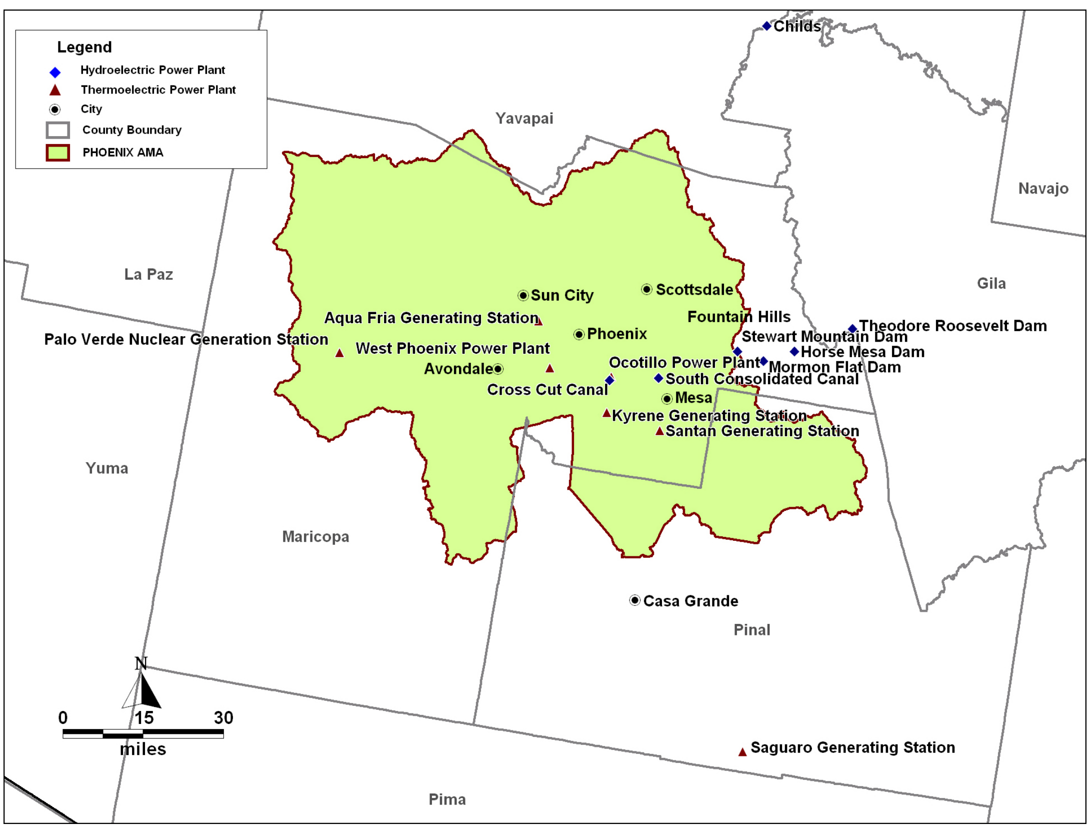


Figure 5-2
Phoenix active management area, showing county boundaries, cities, and locations of major thermoelectric and hydroelectric power plants.

Water Demands

Water is currently used in the Phoenix AMA for irrigation (both Indian and non-Indian), municipal uses (residential, non-residential, and urban irrigation), and industrial uses (cooling, turf, and other uses). The water demand for each of these sectors in 1995 was calculated using information from the Arizona Department of Water Resources (ADWR), and in some cases, using simplified use information as described below:

- **Municipal Use:** 238 gallons per capita per day for Indian and non-Indian population of 2.5 million
- **Urban Irrigation:** Applied at 3.1 acre-feet per acre over an area of 46,000 acres
- **Indian Irrigation:** Applied at 3.8 acre-feet per acre over an area of 38,000 acres at 63% efficiency
- **Non-Indian Irrigation:** Applied at 3.8 acre-feet per acre over an area of 162,000 acres at 67% efficiency
- **Other water demands**, estimated by ADWR include: turf use, 49,000 acre-feet, thermoelectric cooling use, 53,000 acre-feet, other industrial uses, 30,000 acre-feet, and canal losses, 85,000 acre-feet.

The total estimated demand for 1995 is 2.2 million acre-feet, distributed among the different sectors as shown in Figure 5-3. Irrigation is the most significant water use, followed by municipal demands. As of 1995, thermoelectric cooling and other industrial demands were roughly 5% of the total demand. (Note: In ADWR terminology, turf water use is also considered to be an industrial use. In calculations we present in this chapter, turf use is listed separately.) Compared with the national distribution of water withdrawal, the Phoenix AMA is different primarily in that the proportion of municipal demand (roughly corresponding to the domestic and commercial demand in Figure 2-1) is much higher, and the proportion of industrial and cooling water demand is much lower.

Water Sources

Water to meet the needs of Phoenix AMA originates in the renewable regional water sources (Salt River, Verde River, Gila River, and Agua Fria River), imported Colorado River water (through the Central Arizona Project, or CAP, aqueduct), and groundwater. The annual average distribution of the three major sources for 1995 are shown in Figure 5-4 (total freshwater supplies equal 2.2 million acre-feet). A small fraction of the total use is met through effluent water, but this is not considered a new source, and equals about 0.1 million acre-feet.

The distribution of water sources by use is shown in the box-and-arrow diagram in Figure 5-5, constructed largely using data from ADWR. The figure presents a snapshot of water supply and use in 1995, and shows, for example, that municipal demand and irrigation demand are met through a combination of surface water, groundwater, and CAP water. Thermoelectric cooling use is met through groundwater and effluent (used in the Palo Verde nuclear power plant).

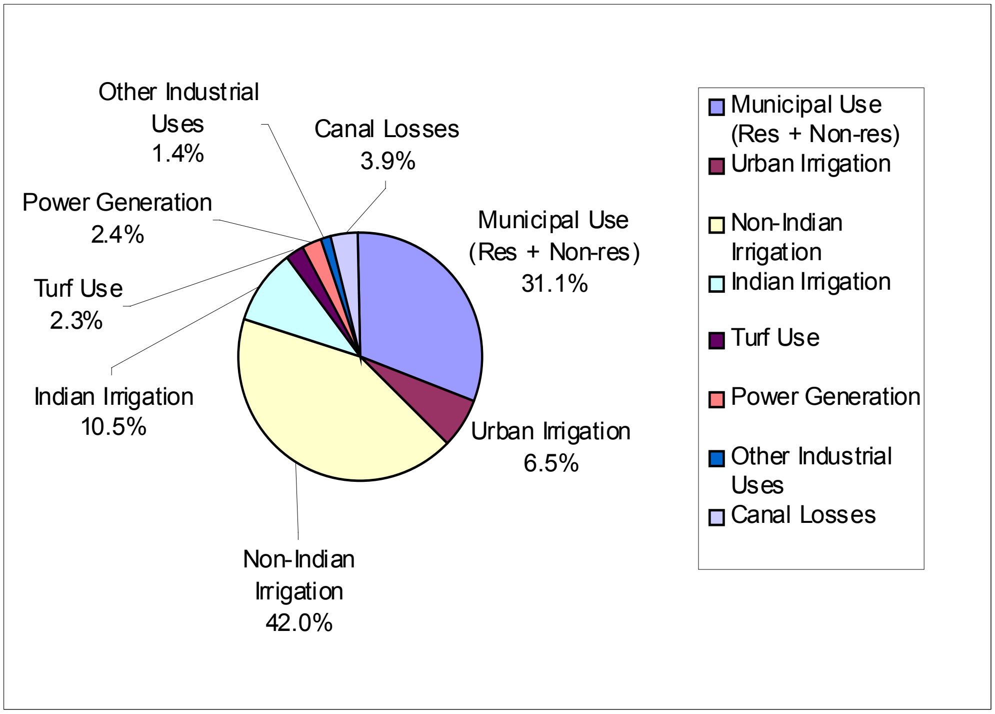


Figure 5-3
Distribution of water demands in the Phoenix active management area in 1995. Total demand equals 2.2 million acre-feet. Data obtained from the Arizona Department of Water Resources.

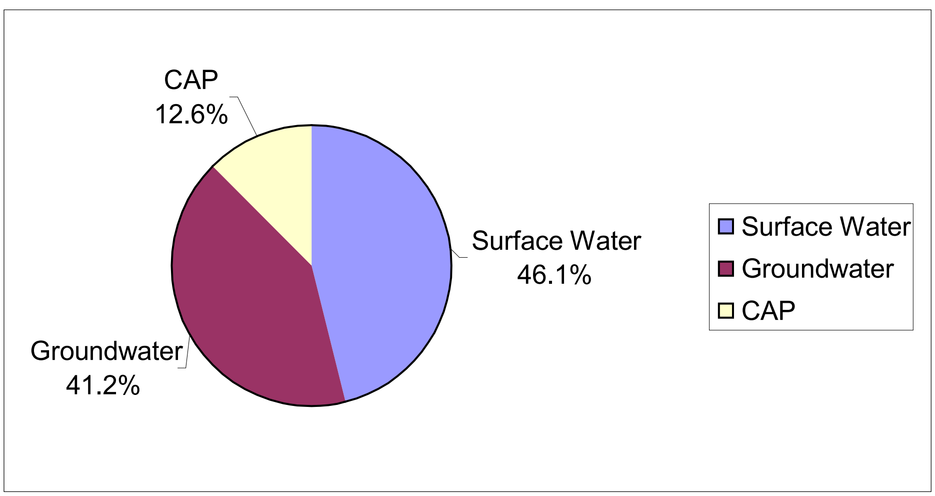


Figure 5-4
Distribution of water sources in the Phoenix active management area for 1995. Total supply equals 2.2 million acre-feet. Data obtained from the Arizona Department of Water Resources.

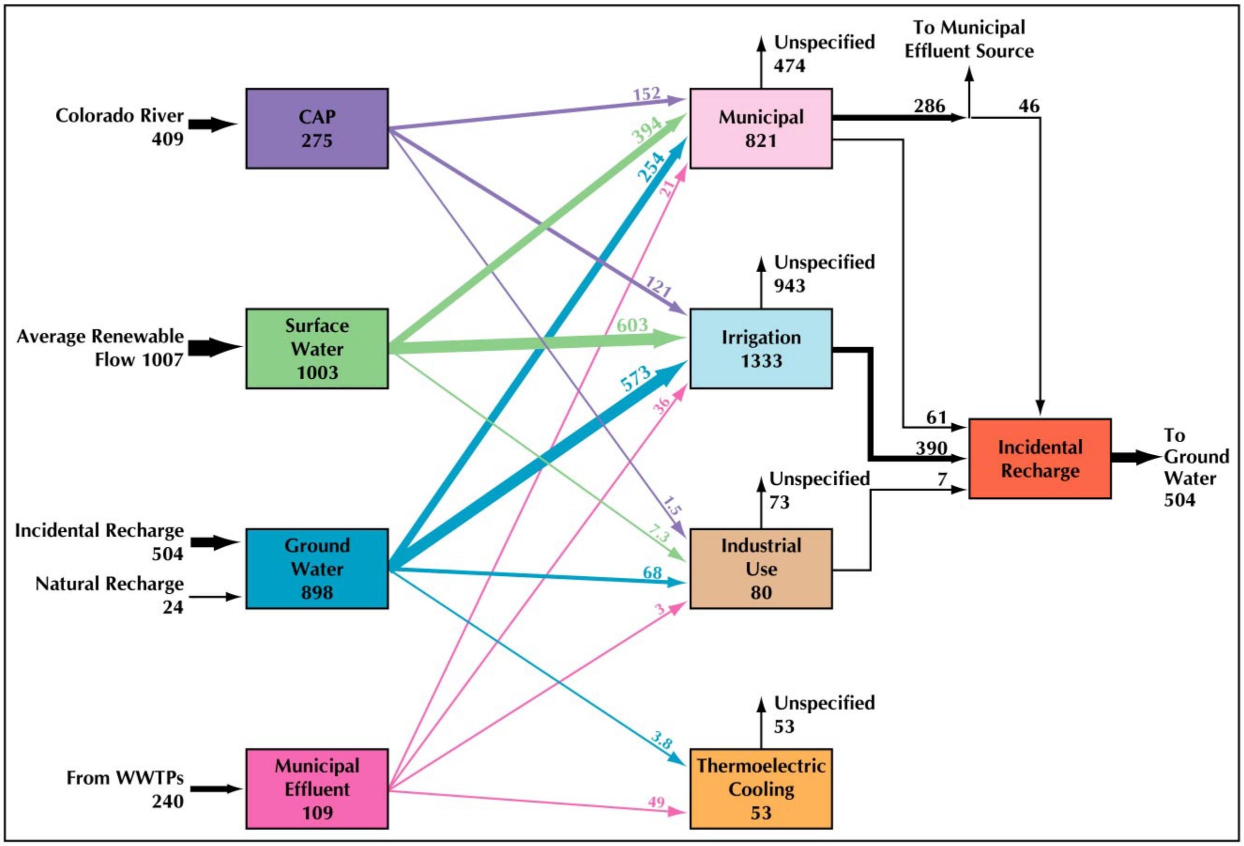


Figure 5-5
Mix of water sources, uses, and incidental recharge of groundwater in the Phoenix Active Management Area for 1995 (all numbers are in units of thousand acre-feet). The boxes represent distinct sources and uses of water. The arrows indicate the withdrawals of water from different sources, and are approximately proportional to the magnitude of the withdrawal. The numbers inside the source boxes on the left equal the sum of the withdrawals represented by the outward arrows. The numbers in all other boxes equal the total use, i.e., the sum of numbers on the arrows pointed toward the boxes. Data obtained from the Arizona Department of Water Resources.

Effluent is also used for irrigation and municipal use, but is a comparatively small source. The diagram also shows that some of the water uses, particularly irrigation, result in a substantial incidental recharge of the aquifers beneath Phoenix AMA, a little over 500,000 acre-feet annually. Because of the arid climate of the region, incidental recharge of the aquifer exceeds natural recharge by a factor of twenty. The left-hand side of the figure shows the maximum available supply and the amount that is used from each of the sources in each box. Thus for CAP supplies, about two-thirds of the total potential supply for 1995 is being used; for surface water, all of the available supply is used; and for effluent water, less than half of the available supply is used. Groundwater supplies stand out in that the withdrawal is much larger than the natural and incidental recharge. The difference, a groundwater overdraft of 400,000 acre-feet annually, is a key water sustainability concern for the Phoenix area.

Future Water Supply and Demand

Based on the snapshot for 1995 that is presented above, it is possible to make some projections of water sustainability in the Phoenix AMA in coming years, considering the variability in supply availability and the changing demands.

Surface water flow variability was estimated by obtaining daily flow data from the four major rivers feeding the Phoenix AMA: the Salt River, the Verde River, the Gila River, and the Agua Fria River. Other streams also enter the AMA, but the flows in them are negligible. The locations of the gauges used for computing inflowing surface water are shown in Figure 5-6. Most of the gauges are below dams with substantial storage capacity (more than 2 years of average flow can be stored), and the flows that enter the AMA are thus highly managed. The total inflow over 1940-2001 is shown in Figure 5-7. The data show that for 22 of these 62 years, the volume of surface water entering Phoenix AMA was lower than the 1995 surface water withdrawal. In general, compared to flows in 1980-1995, flows were much lower from the 1950s to the mid-1960s. More recently, flows from 1999 onwards have been lower than 1995 withdrawals.

Supplies from the Colorado River are also susceptible to variability because the CAP allocation is junior to all other rights on the river. According to the Colorado River Compact, 7.5 million acre-feet *each* of water are allocated to the upper and lower basin states. The allocations for the three lower basin states are: California 4.4 million acre-feet, Arizona 2.8 million acre-feet, and Nevada 0.3 million acre-feet. However, in years when less water is available, the allocation is at the discretion of the Secretary of Interior, with allocations to be administered to assure 4.4 million acre-feet for California, and rights in Arizona and Nevada prior to the Central Arizona Project (Colorado River Basin Project Act, 1968, ADWR, 2000b). It is conceivable that with increasing withdrawals in the upper basin states, in low flow years, Arizona would not get its share of the CAP allocation. Withdrawals in the upper basin states are such that the minimum ten-year flow for the downstream states is 75 million acre-feet at Lees Ferry, Arizona, the station upon which the Compact is based. Annual flows below 7.5 million acre-feet at this station in the Colorado River sometimes occur (Figure 5-8) and may increase in frequency with increasing use in the upper basin states. A plot of annual flow in the Colorado River and the total streamflow into Phoenix AMA (Figure 5-9) does not show a meaningful correlation, which is significant because it implies that years of low flow in both river systems simultaneously are not very likely, at least over the 60-year record presented here. Colorado River supply shortfalls are especially likely during droughts that last longer than 4 years because two main reservoirs on the river, Lake Mead and Lake Powell, can store more than 4 years of average renewable flow, and provide a buffer for droughts of shorter duration. Yet another potential constraint on Colorado River withdrawals may result from the presence of endangered fish species in the Upper and Lower Basins.

Arizona has a number of schemes to improve the management of water in the Phoenix AMA, that reflect the scarcity of this vital resource:

- There is a broad ongoing effort to replace unsustainable groundwater use with renewable supplies, such as CAP water and effluent.

- Unless a plot of land was irrigated between 1975 and 1980, no new irrigation is permitted with groundwater. This restriction does not apply to Indian lands.
- CAP water can only be used for irrigation on land that was irrigated in the past between 1958 and 1968.
- New municipal developments are expected to demonstrate an assurance of a 100-year water supply, with a maximum of 4% being mined groundwater, the remainder being renewable supplies.

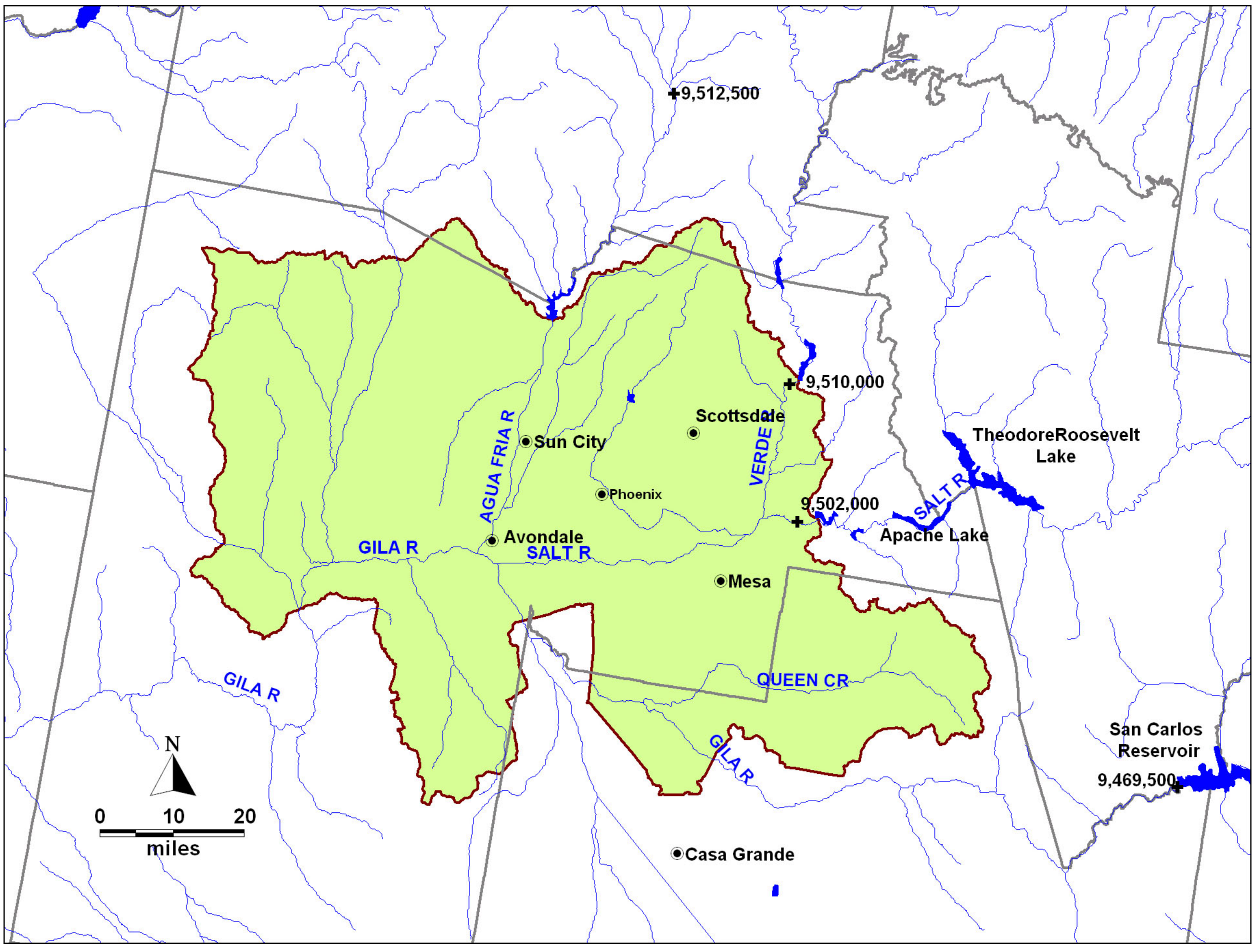


Figure 5-6
Streamflow gauges (shown with the + symbol, along with their USGS identifiers) used to calculate inflow of surface water into the Phoenix AMA. Streamflow stations were chosen based on their proximity to the AMA boundary (primarily the Salt, Verde, Gila, and Agua Fria Rivers), and the length of streamflow record. Also shown on the map are the surface water reservoirs on the main rivers.

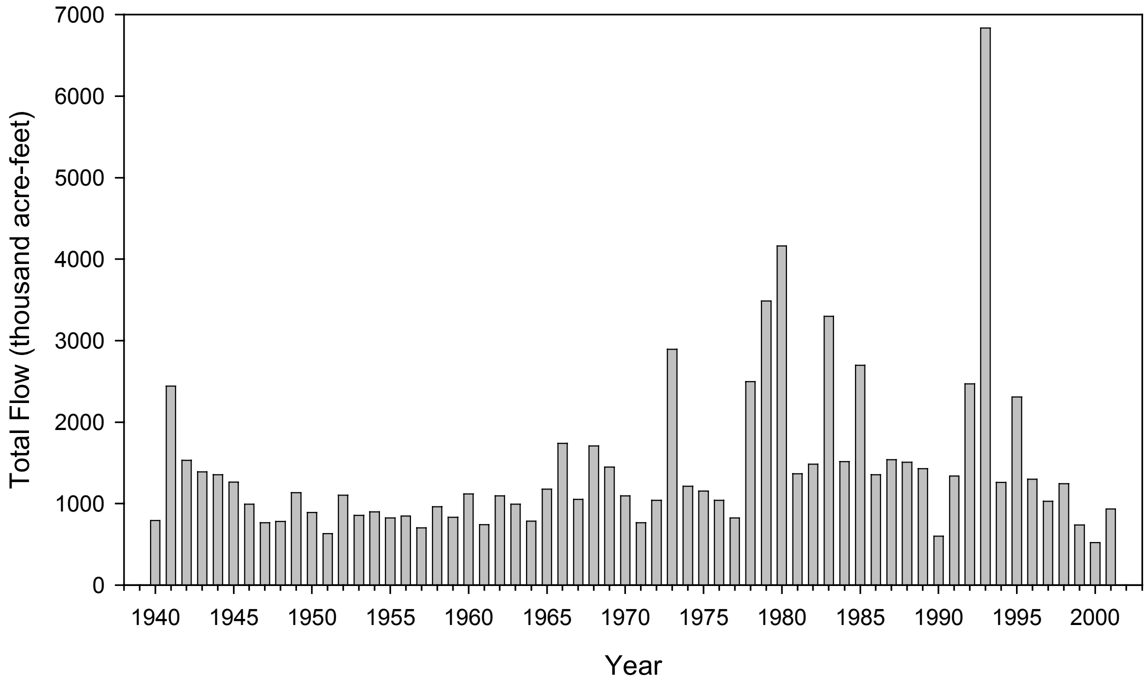


Figure 5-7
Variability of streamflows entering the Phoenix AMA. Annual flows computed from stations on the Salt, Verde, Gila, and Agua Fria Rivers shown in Figure 5-5.

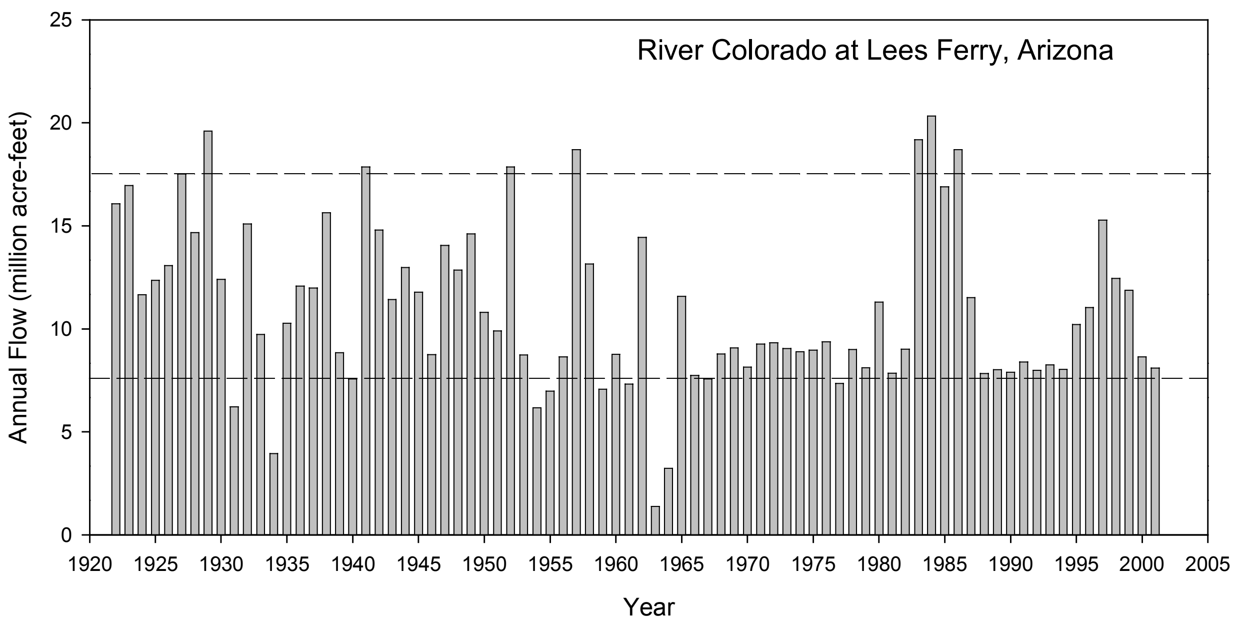


Figure 5-8
Variability of Colorado River flow at Lees Ferry, Arizona, the location that is the basis for distribution of waters in the Colorado River compact of 1922. Also shown in the plot are lines corresponding to 7.5 and 15 million acre-feet, the flows allocated to the lower basin states (California, Arizona, and Nevada) and the total allocated flows, respectively.

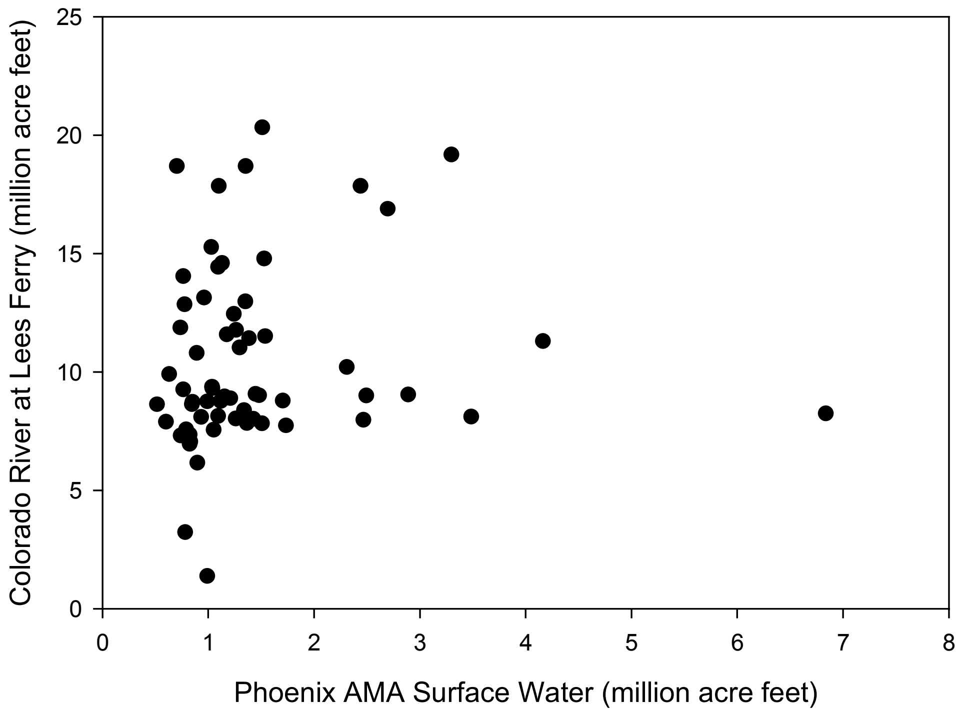


Figure 5-9
Comparison of annual flows at Colorado River at Lees Ferry and the combined annual flows of streams entering Phoenix AMA. When both flows are low, water supply stresses on Phoenix AMA are likely to be most severe.

- A recharge program (Arizona Water Banking Authority) banks unused CAP and effluent water in aquifers for future withdrawal.
- Withdrawal permits for municipal and industrial use include conditions to improve the efficiency of use and to promote conservation.
- Groundwater withdrawal rights for irrigation and non-irrigation uses can be transferred to new uses, thus permitting modifications in the inter-sectoral mix of water use.

Despite these measures, key factors associated with water use, such as population and planned irrigated area, indicate that future water demands in Phoenix will continue to increase.

Figure 5-10 shows the expected change in population, non-Indian and Indian irrigated land, and urban irrigated area from 1995 to 2025, as anticipated by ADWR. Although non-Indian irrigated areas are expected to decrease in the face of continuing urbanization, Indian areas are expected to increase land under irrigation.

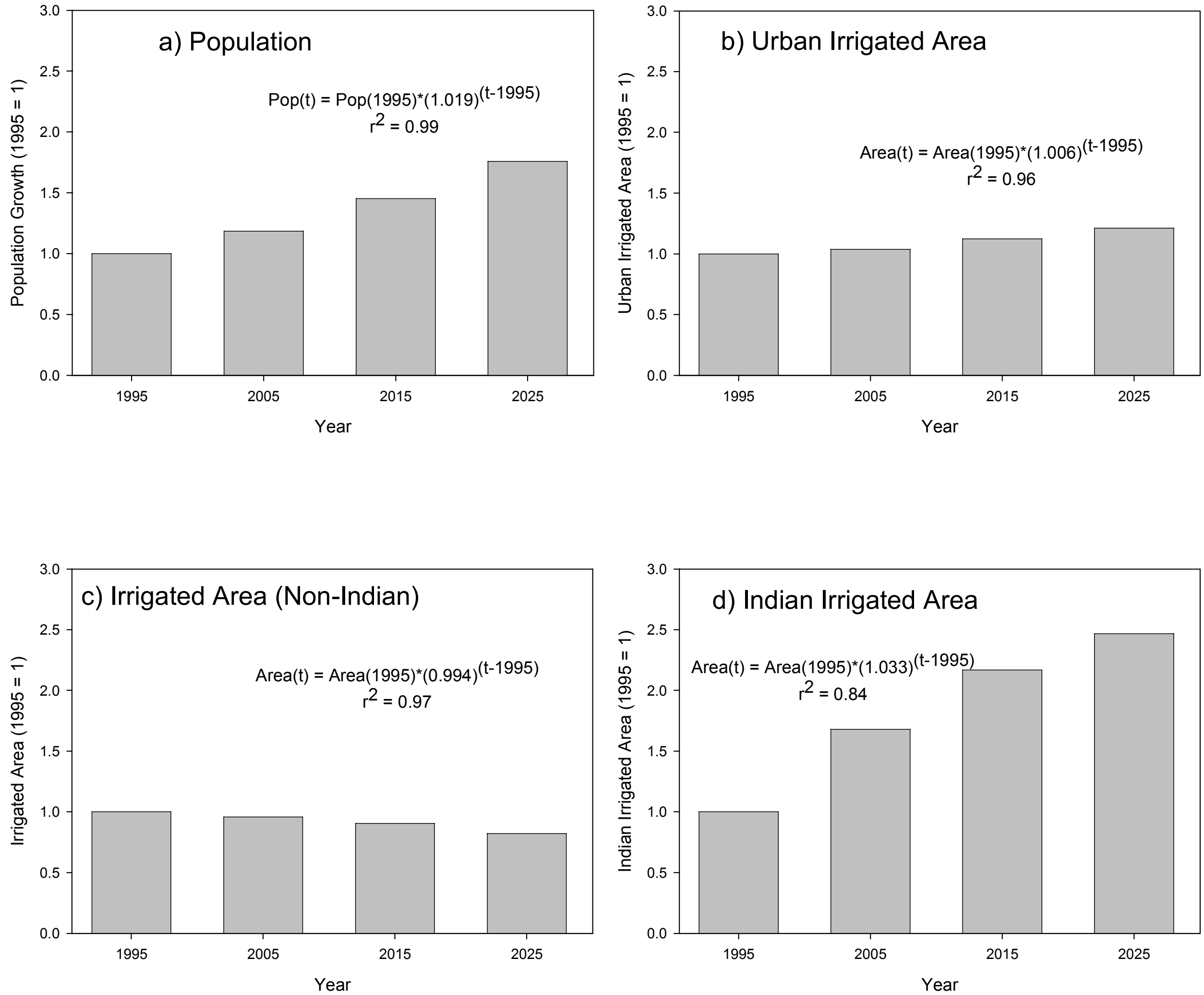


Figure 5-10
Future trends in factors affecting water use in Phoenix AMA: a) population, b) urban irrigated area, c) non-indian irrigated area, and d) indian irrigated areas. All plots are normalized to their 1995 values (1995 =1). Data from ADWR (1999).

In 1999, during the development of the Third Management Period Report, ADWR expected that no new thermoelectric plants would be set up in the Phoenix AMA over 1995-2025, and that increased power needs would be met through imports. More recent data shows this not to be thecase: the Phoenix area is expected to develop substantial new power generation in the coming decade, with Maricopa County adding the most number of plants in the state (Walls, 2000). In fact, the area around Palo Verde nuclear power plant, west of Phoenix, is expected to be home to 12,000 MW of generating capacity, one of the largest concentrations of power generation capacity anywhere in the nation (Holmes et al., 2002). Table 5-1 shows the proposed power generation units in Maricopa County, and their water requirements. Total projected water withdrawals for power generation from 1995 to 2015 is shown in Figure 5-11, indicating a doubling of water use corresponding to the nearly four-fold increase in power generation. Much of this new water will be groundwater obtained from retired irrigation rights (Arizona Water

Resource, 2001a). Not all of the new power generated would be used for the Phoenix area; power is expected to be exported to other states, such as California and Nevada (Arizona Water Resource, 2001b).

Based on water use rates described earlier for municipal and irrigation use, and using the revised estimates of thermoelectric withdrawal, we project future total water demand in Figure 5-12. This calculation indicates a nearly 50% increase in water demand over 1995-2025. Although we have used some simplifying assumptions, such as the constant use rates in comparison with the ADWR's Third Management Period Report (ADWR, 1999), the net results are similar. Total demand is projected by ADWR to increase to 2.9 million acre-feet by 2025 assuming thermoelectric withdrawals at constant 1995 levels, compared with our estimate of 3.1 million acre-feet, considering more realistic thermoelectric withdrawals. The overall result is largely a consequence of increased population and increases in Indian irrigation, which more than compensate for any reductions in withdrawal by non-Indian irrigation. Should all of the proposed efficiencies in the Third Management Plan apply, the total demand is expected to be 2.6 million acre-feet (ADWR, 1999). About two-thirds of this reduced demand of 300,000 acre-feet is because of improved efficiency of non-Indian agricultural use, and about one-third is due to improved efficiency of municipal use. However, the improved efficiency of agricultural use has the effect of reducing the incidental recharge, and therefore the groundwater overdraft for the current use scenario and the Third Management Plan improved efficiency scenario, is broadly similar, and is somewhat greater than 400,000 acre-feet.

Consequences for Phoenix AMA

An outstanding feature of the Phoenix AMA is the extent to which its surface and groundwater resources are developed. This has two main consequences: in the short term, the area is subject to more economic disruptions during drought years, and in the long term, there is the ongoing concern associated with unsustainable groundwater overdraft.

Arizona does not have a state-level drought plan although one is currently being developed (Governor's Drought Task Force, 2003). Planning for droughts is often done by water agencies and municipalities. The available responses are to increase groundwater pumping, import water from elsewhere (in this case from CAP), or to cut supplies and enforce mandatory conservation. Beginning in 1999, for example, surface water inflows into the Phoenix area have been below average, with the year 2002, having the lowest flows on record, and Arizona is having its severest drought since attaining statehood in 1912 with planned reductions in water use (City of Phoenix, 2003). In general, the key feature of drought responses is that although they are highly disruptive, they are short-term adjustments (e.g., City of Phoenix Drought Management Plan, 2002), rather than long-term modifications of water use. The potentially severe effects on the Phoenix AMA of 1-year, 5-year, and 10-year droughts, based on surface water flow information from the paleo and historical records, have been explored by Carter et al. (2000). In general, more severe groundwater overdrafts and associated problems are likely to result during the drought years.

Table 5-1
Arizona to Add Substantial New Thermoelectric Power Generating Capacity[1]

Facility	Technology	Fuel Type	Output (MW)	Est Online Date	Water Use (acre-feet/yr)	Company	Water Source	Notes
West Phoenix Temporary	GT	Gas	99	7/1/2001		Arizona Public Service		Complete
Saguaro Temporary	GT	Gas	99	7/1/2001		Arizona Public Service		Complete
APS Upgrades and Reactivate		Gas	203	7/1/2001		Arizona Public Service		Complete
West Phoenix (Phase 1)	Combined	Gas	120	8/1/2001		APS/Calpine		Complete
Arlington Valley I	Combined	Gas	580	8/1/2002	3400	Duke Energy NA		Complete
Redhawk 1	Combined	Gas	530	9/1/2002	3325	APS	Effluent	Complete
Redhawk 2	Combined	Gas	530	9/1/2002	3325	APS	Effluent	Complete
Kyrene	Combined	Gas	250	9/1/2002	1600	Salt River	Effluent	50% Complete
West Phoenix (Phase 2)	Combined	Gas	530	6/1/2003		APS		75% Complete
Mesquite Power I	Combined	Gas	630	7/1/2003	3750	Sempra Energy Resources	Groundwater	75% Complete
Gila River I	Combined	Gas	580	7/1/2003	2500	Panda Energy/TECO	Groundwater	75% Complete
Gila River II	Combined	Gas	580	7/1/2003	2500	Panda Energy/TECO	Groundwater	75% Complete
Harquahala Generating Station	Combined	Gas	1040	9/1/2003	6400	PG&E NEG	CAP	75% Complete
Mesquite Power II	Combined	Gas	630	1/1/2004	3750	Sempra Energy Resources	Groundwater	25% Complete
Gila River III	Combined	Gas	580	1/1/2004	2500	Panda Energy/TECO	Groundwater	50% Complete
Gila River IV	Combined	Gas	580	1/1/2004	2500	Panda Energy/TECO	Groundwater	50% Complete
Gila Bend	Combined	Gas	845	6/1/2004	7500	Power Dev Ent	Groundwater	Pending siting
Santan	Combined	Gas	825	5/1/2005	6500	SRP	CAP	
Redhawk 3	Combined	Gas	530	6/1/2006	3325	APS	Effluent	Merchant
Redhawk 4	Combined	Gas	530	12/1/2007	3325	APS	Effluent	Merchant
Tonopah	Combined	Gas	1100	1/1/2011		PG&E NEG/Shaw		
Arlington Valley II	Combined	Gas	600	1/1/2011	3400	Duke Energy NA	Groundwater	
Total			11991		59600			

[1] Source: California Energy Commission, 2003 (http://www.energy.ca.gov), for generation capacity and other sources for water uses/sources.

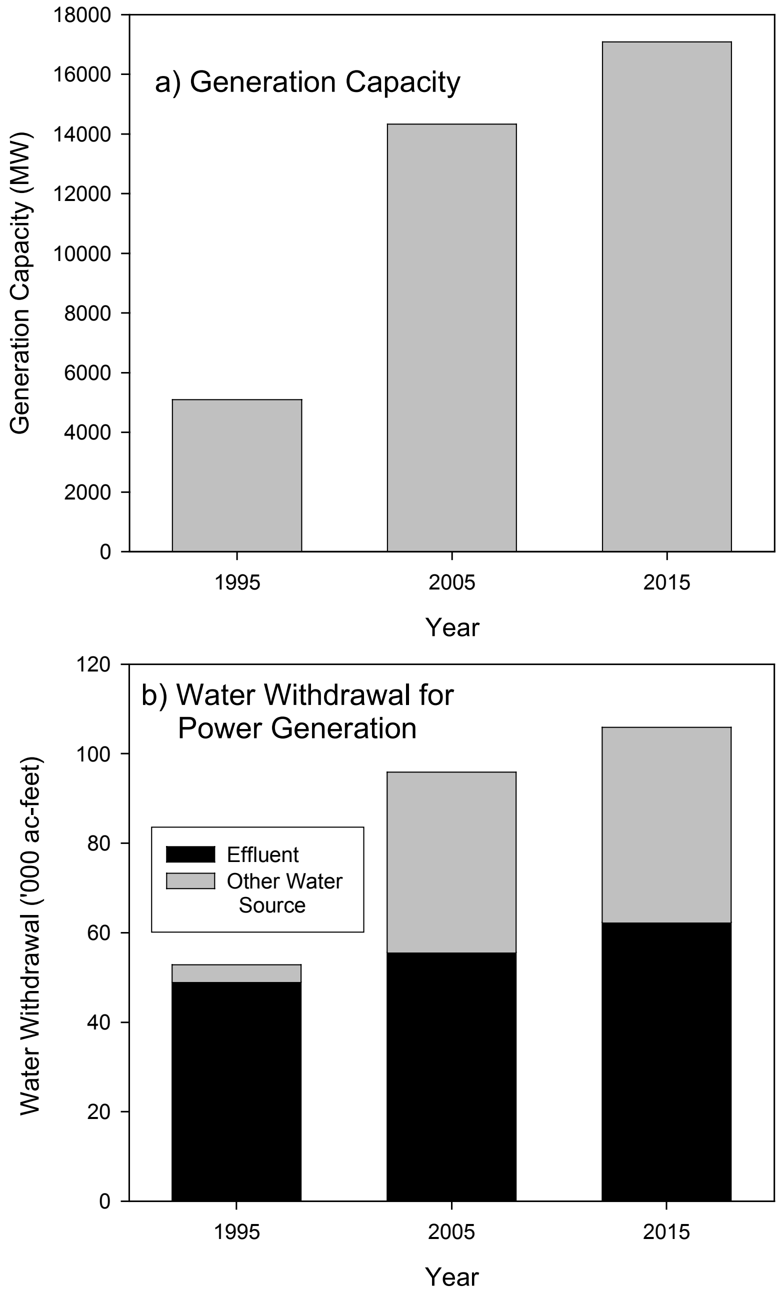


Figure 5-11
Future trends in a) power generation, and b) water withdrawal for power generation in Maricopa County. Growth in power generation is much larger than predicted by EIA for the pacific region in general, and is in contrast with third management plan expectation of no new generation in Phoenix AMA over 2000-2025. Data for 1995 are from the penwell database; projected generation data were obtained from the California Energy Commission; water use data from the Arizona Water Resource (2001) and the Arizona Department of Water Resources.

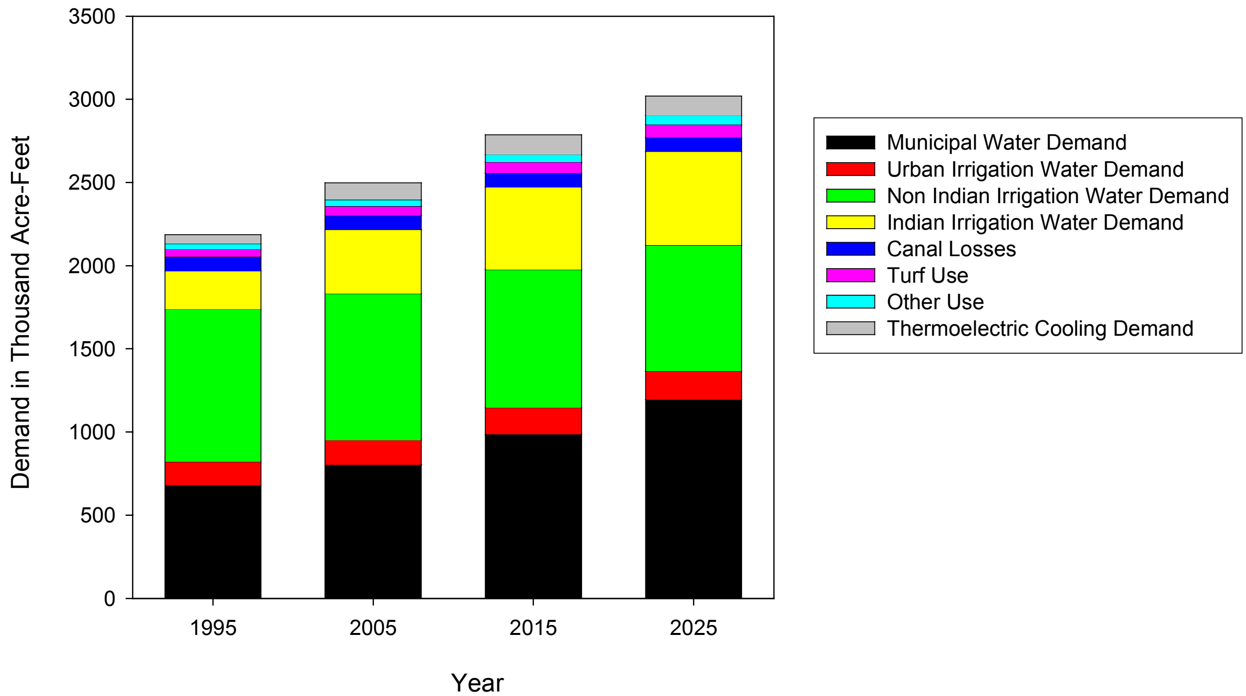


Figure 5-12
Future trends in water withdrawal in Phoenix AMA based on the factors shown in Figures 5-10 and 5-11.

Over the long-term, ADWR has undertaken considerable efforts to reduce the dependence on non-renewable groundwater use since the inception of the Groundwater Code in 1980. A large part of the change has come about because of the availability of the new CAP supplies that became available after 1985. In future decades, it is highly unlikely that there will be major new sources of freshwater to meet the needs of the Phoenix AMA. Perhaps the only source of water that is expected to grow in future years and is now underexploited is municipal effluent (Figure 5-13). Water users that can substitute treated effluent (such as for irrigation and industrial use) for freshwater will find this to be a more secure source. However, as currently projected by ADWR, effluent use is expected to increase relatively modestly and only for municipal use; the total use of effluent will constitute only a third of the available amount. Thus, in all likelihood, if the projected growth and water use patterns occur, unsustainable groundwater use of approximately 400,000 acre-feet or more will continue indefinitely. Based on the total AMA area of 5,646 mi^2 and an aquifer porosity of 0.2, this annual overdraft corresponds to a water table decline of about half a foot per year, although it is very likely that some areas will exhibit much greater declines. In ongoing monitoring of wells across the AMA, declines of greater than 10 feet have been seen in some areas within the AMA over 1995-2000, particularly in areas near irrigation pumping wells (ADWR, 2002). Over time periods of decades, the cumulative declines are expected to be significant, with associated problems of subsidence, increased pumping costs, and poor groundwater quality.

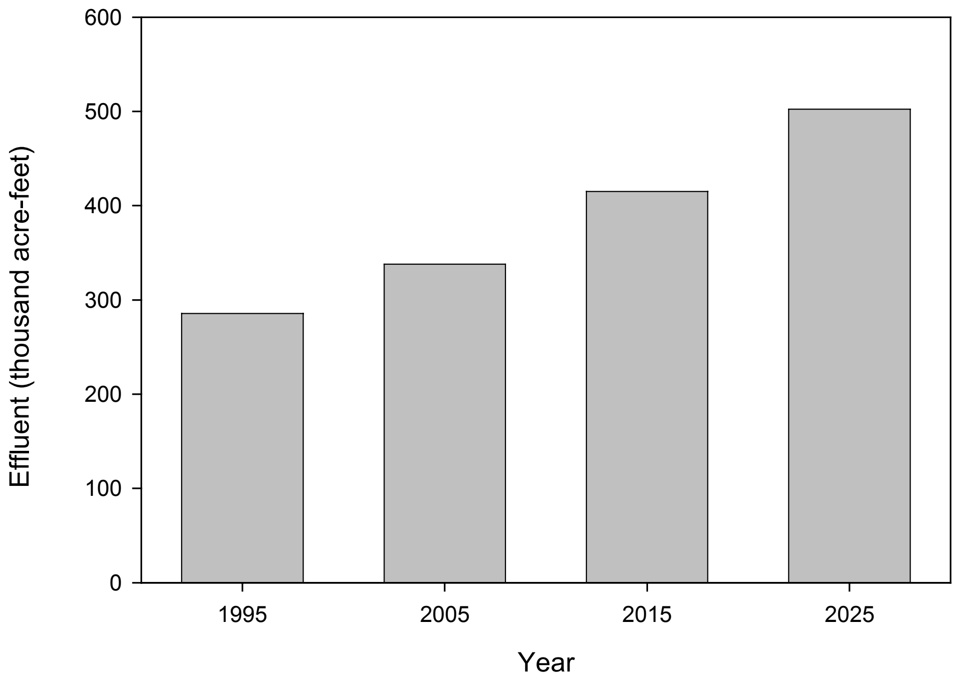


Figure 5-13
Projected volumes of municipal effluent in the Phoenix AMA, based on population growth shown in Figure 5-10, and assuming effluent generation of 100 gallons per capita per day.

Aquifer recharge using renewable supplies provides a means to store water in high flow years for use in low flow years, and serves as an underground reservoir similar to those created by dams. In the Phoenix AMA, the water banking program is fairly successful, and as of 1998, more than 1 million acre-feet of water had been stored in this manner (ADWR, 2000a). This stored water can provide a buffer for year-to-year variations in surface-water supply, and provides some protection from droughts. Only a small amount of the total stored water (5%) is permanently set aside for the aquifer. It does not therefore, correct for the systematic overdraft that happens every year, including in years of average surface water supply. Unless more stringent measures are taken to greatly improve water use efficiencies beyond current proposals in the Third Management Period, or to curtail some types of water use, groundwater withdrawals will not attain the Arizona Groundwater Management Code goal of sustainability by the year 2025.

The large increase in proposed power generation in the Phoenix AMA, with potential new water demands on a system that is already stressed by limited water availability, is unusual. However, the same factor that stresses water supplies, population growth, also causes increased electricity demands. Although the ADWR proposed in 1999 that new power needs would be met through imports, it is unclear today where these imports would come from, particularly in light of the electricity shortages of 2000-2001 in the western region. Therefore, from the standpoint of economic security of the region, the current moves to increase power generation capacity, despite the limits on water availability, are not surprising. A key feature of water use for thermoelectric generation in Maricopa County is the relatively high efficiency of current water use. Freshwater withdrawal in Maricopa County is 128 gallons per megawatt-hour of electricity generation (Consumptive Use = 34 gallons/Mwh), among the lower values of freshwater use in non-coastal areas nationally. Furthermore, some of the water needs are met through the use of effluent (as in the Palo Verde Nuclear Power Plant) and through the use of retired irrigation rights. Municipal effluent, as we have discussed earlier, is a fairly secure supply in the Phoenix AMA, whereas the change from irrigation to power generation use reflects a long-term shift in the economy of the region.

Of the 19 newly proposed power plants in Arizona in 1999, only one planned to use dry cooling, and this project is now on hold (Arizona Water Resource, 2002). The primary reasons for the preference towards wet cooling are greater efficiency in hot areas and lower capital costs of these systems and also the limited large-scale experience with dry-cooling and hybrid wet/dry cooling systems. For dry cooling to become more widely accepted in the future there needs to be better data on the performance penalty of these systems under a range of climatic conditions, and also the additional capital and operational costs associated with implementing these systems (Micheletti and Burns, 2002). A recent EPRI report (EPRI, 2002b) addresses this issue and provides capital cost comparisons for wet and dry cooling technologies in different potential sites in California representing a range of climatic conditions. It appears that dry cooling systems have initial capital costs at least 5 to 10 times more than wet cooling systems, and there is an operational penalty as a result of higher energy costs to operate the system. There is less detailed information on the differences in operations and maintenance cost, although they are thought to be similar for the wet and dry-cooled systems. Thus, dry cooling systems are likely to be practical only in areas with severe water limitations.

Implications for Other Areas of the Country

Phoenix is perhaps an extreme case of a region with almost fully developed sources of renewable water supplies, that will face conflicts caused by increasing population and related demands on the one hand, and protected water rights over existing limited supplies on the other hand. However, in many respects, the conditions may apply elsewhere in the country. Demands, driven by population, will continue to increase, and conflict with existing, legally protected, water uses. Additional withdrawals may be limited, not by the availability of water, as in the Phoenix AMA, but by legal and institutional requirements for instream use. In the Phoenix AMA, practically all available water is allocated for human use but other states may have specified minimum flows for ecological benefits. Thus, elements of the management strategy being employed in Arizona may have to be emulated more widely in other parts of the country. This includes the construction of detailed water budgets, real-time monitoring of groundwater levels, unified management of surface and groundwater resources, evaluation of sustainability of these resources, the use of groundwater storage and recovery for supply during dry years, the ability to transfer historical rights to new uses, constraints on new water use, the use of effluent waters, and the AMA-wide conservation program for municipal, industrial, and agricultural uses.

The dramatic increase in power generation capacity, despite known stresses on water use, is also likely to occur more widely across the US, as regions seek to meet new electricity demands, and improve the reliability of existing systems. In the absence of experience and detailed information of costs associated with dry cooling, areas that are not as water-short as Phoenix may not feel the pressure to invest in this technology, and water supply and electricity generation growth will remain closely inter-related.

6
A NOTE ON THE POTENTIAL IMPACTS OF CLIMATE CHANGE

The potential impact of climate change on water resources at the local, national, and continental scales has been studied extensively, both qualitatively and quantitatively. Although the focus of some of the studies are on extreme events such as flooding that may be caused by higher intensity rainfall and hurricanes, many have focused on water supply (Arnell, 1999; Blake et al., 2000; Boland, 1997; Chang et al. 1992; Glieck, 2000; Diettrick et al., 1999; Hurd et al., 1999; Murdoch et al., 2000; Strzepek, 1999; Vogel, 1997 and Vorosmarty et al., 2000). In fact, the majority of studies of future water resources sustainability have considered climate change as the principal driving force.

That climate change, with implied changes in temperature and precipitation, will have a major effect on water resources is a foregone conclusion. 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 the most critical effects of climate change. From the perspective of the framework presented in this report, calculations to assess future water sustainability using the approaches described in Chapters 2-4 are straightforward if expected changes in the temperature (and therefore evapotranspiration) and precipitation can be obtained from global general circulation models (GCMs). Climate data used in the analysis presented in Chapter 2 and 3 can be replaced by model outputs from GCMs to assess the impacts of specific climate change scenarios on water resources. Despite all this, we chose to not include climate change in our assessment of water resources sustainability primarily because of the wide variability in forecasts of precipitation.

For illustration, we compared outputs from three widely quoted GCMs for the IS92a CO_2 emission scenario: Hadley Centre Unified Model (UK), National Center for Atmospheric Research Model (DOE), and the Geophysical Fluid Dynamics Laboratory (GFDL) (output data obtained from Hulme et al., 2000). Comparison of outputs shows that the models generally agree on the temperature increase, with all three models indicating increases in temperature over the US. However, the models diverge substantially when changes in precipitation are compared, with both *significant increases and decreases* being predicted for the US. The precipitation predictions clearly highlight the limited usefulness of the GCMs in their current form for water resource managers who may be charged with developing a response to future climate change. Significant increases and decreases in precipitation both create unique problems, with possibly different responses. A possible area of future research, of particular interest to water resource managers, could be to identify the reasons underlying the disagreement in precipitation predictions from the different models. Note that increases in both temperature and precipitation are supported by data from the past few decades.

Given the uncertainty in model predictions, particularly with respect to precipitation, we think it is premature to make quantitative assessments of the impacts of climate change on water resources on a national scale. Although several such studies have been published that attempt to evaluate these impacts, these studies are either local in scope or are not quantitative. 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 US that are likely to be water stressed in the absence of climate change, as presented in Chapter 4, are going to be even more vulnerable in the event of climate change leading to reduced precipitation.

7 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 US, agricultural withdrawal and thermoelectric cooling withdrawal are the major components of total freshwater withdrawal (40% and 39%, respectively). Of these two withdrawals, agricultural water is largely used consumptively, and on a national basis 82% of the total consumptive use is for agriculture, in comparison with 3% of total consumptive use for thermoelectric cooling. Public domestic withdrawal and consumptive use is about 7% of the total. Review of water use data from 1975-1995 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%. The improved efficiency of water use for electricity generation is notable: a 40% increase in generation over 1975-1995 was accompanied by practically no change in freshwater withdrawal. Using the annual water withdrawal, we also developed an approach 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 US, including areas that are not normally thought of as water-short.

Future water requirements for the US, at the spatial resolution of counties, were estimated using population growth in the US over 2000-2025, extrapolated from trends over 1990-2000, and electricity demand increases over 2000-2025, forecast by the Department of Energy. Two scenarios were studied: a business-as-usual scenario where the rates of water use remain at their 1995 values over 2000-2025, and an improved efficiency scenario where annual improvements in water use efficiency (based on 1975-1995 data) were used to estimate future requirements. The estimates show several areas of the US, 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 year 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.

Two composite indices, incorporating metrics capturing different water use characteristics (water availability, extent of water resources development, sustainable groundwater use, environmental constraints on withdrawal, projected growth in water demand and power generation, growth in demand for stored water) were developed to summarize the information presented in this report: Water Supply Sustainability Index and Thermoelectric Cooling Constraint Index. The first highlights areas where water supply issues in general are likely to be a concern, and the second highlights areas where electricity generation growth may be constrained by available water supplies. Maps of these indices show areas that are suitable for further detailed study of water supply sustainability issues at a finer resolution.

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 ourselves to using available national-scale data at the finest resolution possible, we aimed to create a framework for evaluating water sustainability, but one that could be used to provide results as are presented in the maps in this report. 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, its approximation of potential storage deficits, and consideration of future demands, particularly for electricity 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, available on the internet at http://www.drought.unl.edu) that can be thought of as a complement to this study. For example, it is stated that about 38 states in the US 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 who must focus on identifying and evaluating the possible use of 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, it is worthwhile to remember a significant part of the national water use database is comprised of estimates of use, rather than actual data, and there may be errors and/or uncertainties in these estimates that may propagate through the analysis presented here. We have attempted to overcome some of the shortcomings of the national data set, by performing a detailed study of water supply and demand in the Phoenix, Arizona area.

The Phoenix area is an important region for detailed study of water sustainability because it is arid and among the fastest growing metropolitan areas in the US. In an average year, less than half the water needs are met through surface water sources, the remainder coming from groundwater and imported Colorado River water, through the Central Arizona Project (CAP) Aqueduct. At historic, current, and projected rates of use over the next two decades, groundwater withdrawals from the aquifers in and around Phoenix, specifically in the designated Phoenix Active Management Area (AMA), are substantially greater than recharge. To meet a legislative goal of ending groundwater overdraft by 2025, the Phoenix AMA develops decade-long plans to enhance water sustainability, the last of which, the Third Management Plan, was published in 1999 to cover the period 2000-2010. Although the completion of the CAP aqueduct by 1985 provided a major new source of renewable water to the region, the dependence on groundwater overdrafts, on the order of 400,000 acre-feet annually, is projected to continue into the foreseeable future. The main reason for the overdraft is the continued pumping of groundwater at high rates as a result of protected groundwater withdrawal rights (e.g., irrigation grandfathered rights and Indian water rights) over which the state has little control, except during brief periods of drought. While there are extensive efforts at recharging groundwater using CAP and effluent water, most of this is for storage purposes, and is intended for later withdrawal. Only a small fraction of the stored water is permanently set aside for the aquifer and counters the annual overdraft. Additionally, proposed improvements in agricultural water use efficiency have the effect of reducing incidental recharge of the underlying aquifers, which is the single largest source of recharge, and thereby increasing overdraft. Perhaps the most noteworthy goal of the Third Management Plan is the attempt to hold groundwater overdraft at a relatively constant level even in the face of rapidly expanding municipal demand. The combination of protected groundwater withdrawal rights over an essentially finite supply on the one hand and rapidly increasing municipal demand on the other hand require legal, institutional, and possibly scientific solutions, beyond what has been currently proposed if the AMA is to attain its goal of sustainable groundwater withdrawal by 2025. Although Phoenix stands out among large cities in the US because of its arid climate, efforts undertaken there may have much wider applicability across the US, as more and more cities face water stresses because of growing populations. These efforts include, for example, extensive aquifer storage and recovery operations for improving water supply during dry years, and the use of effluent for industrial, municipal, and irrigation uses.

This study constitutes a small step toward developing a comprehensive assessment of the state of the nation's water sustainability and the possible impacts on power generation. Although we have developed maps of water sustainability using the best available information today, this information could be significantly enhanced in the future. Information is especially needed in three areas: instream use requirements to maintain optimal habitat and beneficial uses; water storage and withdrawal capacity; 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 1970's. 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 groundwater) 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 cataloged 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.

8
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