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Projecting U.S. freshwater withdrawals

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Abstract. As past attempts to forecast water use have shown, predicting the future is fraught with difficulty. Yet a lesser objective, to extend past trends into the future, can offer a useful look at what may lie ahead. Relying on U.S. Geological Survey water use data for the period 1960–1995, this paper projects U.S. water use based on trends in basic water use factors. Those trends are largely encouraging. Over the past 35 years, withdrawals in industry and at thermoelectric plants have steadily dropped per unit of output, withdrawals per acre have dropped in some irrigated regions, and per capita domestic withdrawals, after rising steadily from 1960 to 1990, dropped in 1995. If these trends continue, aggregate withdrawals in the United States over the next 40 years will stay within 10% of the 1995 level, despite economic growth and an expected 41% increase in population. This projection is in contrast to most previous projections of U.S. water use, which did not adequately account for future improvements in water use efficiency. Important qualifications to these projections are that some regions of the United States, especially the southeast, will experience above average increases and that the projections are for the average year and thus underestimate demands during dry years.

1. Introduction

Off-stream water use in the United States has increased over tenfold during the twentieth century in response to tremendous population and economic growth. As withdrawals have increased, more water has been consumed, leaving less instream flow, just as rising incomes and urbanization have intensified calls for maintaining water-based recreation opportunities and protecting stream water quality [*Gillilan and Brown*, 1997]. Future population and income growth will place additional demands on water supplies. This paper, written in response to the Forest and Rangeland Renewable Resources Planning Act of 1974 (public law 93-378), requiring periodic assessments of expected resource supply and demand conditions in the United States, attempts to project what those future demands will be.

Large-scale projections of water use in the United States have been attempted several times, for instance, by the *Senate Select Committee on National Water Resources U.S. Congress* [1961], by *Wollman and Bonem* [1971] for Resources for the Future, by the *Water Resources Council* [1968, 1978], by the *National Water Commission* [1973], and by *Guldin* [1989] of the U.S. Forest Service. Comparisons of these forecasts have consistently found large differences among them, as well as large discrepancies between projected and actual water use, despite the prodigious effort and analytical rigor applied in some of the studies [*Viessman and DeMoncada*, 1980; *Osborn et al.*, 1986; *Guldin*, 1989]. These large differences highlight the dangers of forecasting, especially without an understanding of the determinants of water use and sufficient data on past water use [*Shabman*, 1990].

Accurate forecasts of future water use are not possible because we know too little about future technological, demographic, and economic conditions. What is possible is to project water use assuming recent past trends in factors that affect water use continue into the future. This study emphasizes projections based on major water use determinants (population, income, electric energy production, and irrigated acreage) in light of information on 1960–1995 trends in water use efficiency. Recognizing the difficulty of forecasting, the overall approach taken here is to limit complexity so that the underlying assumptions are relatively few and their impact on the results is transparent. Although more complex models, containing additional independent variables, could be constructed based on past trends, the added complexity would not improve water use projections unless the additional independent variables could be accurately forecasted. Because any forecasting of model independent variables is essentially educated guess work, additional model complexity is not necessarily helpful. The simple methodology applied here, using the now quite substantial historical record (most earlier efforts to project water use, listed above, relied on a small fraction of the data now available), should produce a reasonably accurate estimate of future water use if past trends continue along their current course and offers a tractable basis for sensitivity analysis.

Future water withdrawals will, of course, also depend on changes in water supply and prices. Changes in water supply depend largely on climate and water management infrastructure. This study will ignore these two influences for the following reasons: First, although the potential for climate change has become a serious concern and has been much studied, little agreement yet exists about the effects of climate change on water availability in specific basins [*Mahlman*, 1997]. In light of this uncertainty it is perhaps not unreasonable to assume a constant climate for this study. Second, future changes in water management infrastructure, to the extent that they occur, are not likely to greatly affect water supply. Growth in water management infrastructure (especially dams, canals, and ground water pumping facilities) during the twentieth century has, of course, greatly expanded the availability of useable water. However, it is generally acknowledged that relatively few opportunities remain, especially in drier regions, for expanding such facilities on a large scale. Further, because of concern

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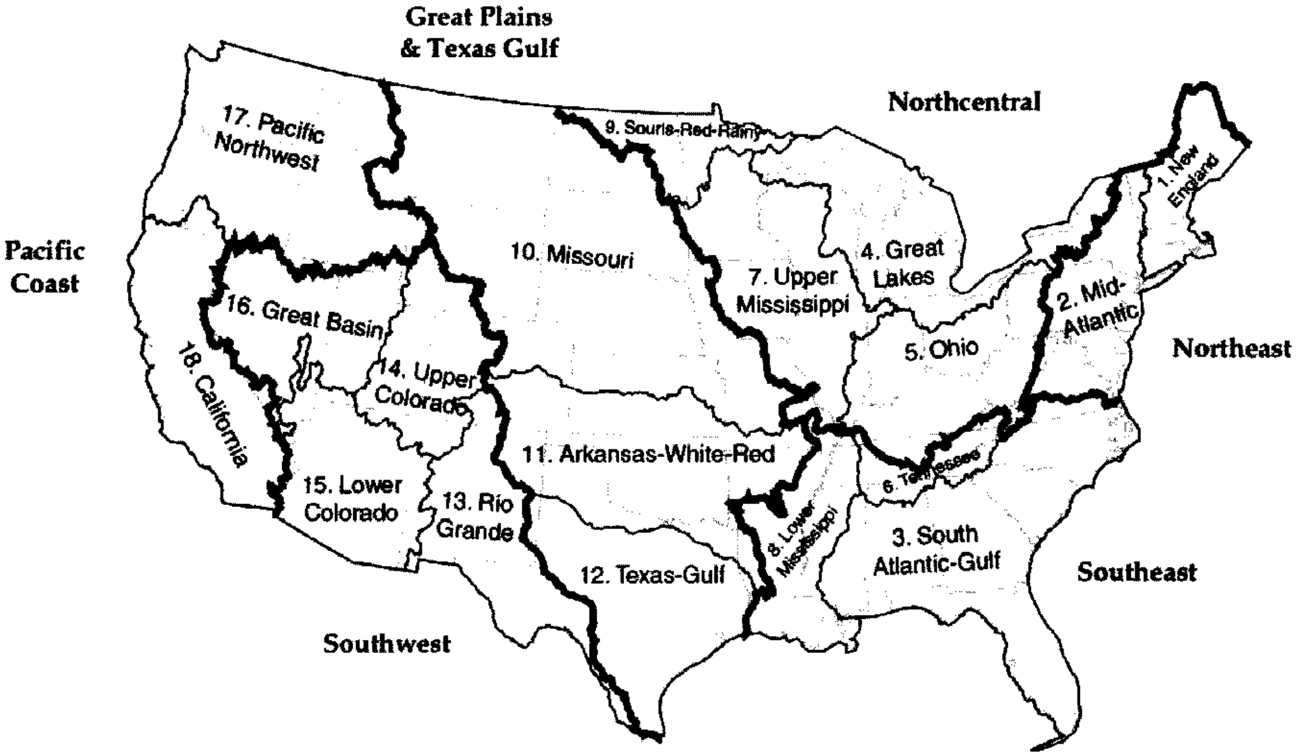

Figure 1. Six aggregated regions and their eighteen water resource regions (WRRs).

over environmental impacts, proposed new developments are carefully scrutinized. In addition, as sedimentation decreases reservoir storage capacity and as pumping lowers groundwater tables, many existing facilities are slowly losing their utility. The additional water development that does occur may only help compensate for these losses. On balance, the assumption of no net increase in total supply is probably reasonable for most parts of the United States.

Because of the powerful effect of price on both water supply and water use, an economic approach was considered for this study. However, an economic model was not adopted, principally because economic demand and supply functions are so difficult to specify for some water uses and for large geographic regions containing numerous market areas. The more modest approach that was adopted largely ignores price (thereby essentially assuming a continuation of past price trends).

Demand for water differs by region depending on climate, population, availability of arable land, reliance on thermoelectric energy, and other factors. The many potential differences among geographic areas suggest that demand for water should be studied at the smallest geographical scale possible. However, isolated small-scale studies, often performed using different variables or methods, do not lend themselves to broad-scale conclusions about regional or national trends. The objective of this paper is to characterize past and future water withdrawals in the entire United States using consistent methodology, making a broad-scale approach essential.

2. Data and Methods

This report relies extensively on water use data for the period 1960–1995 compiled every 5 years by the U.S. Geological Survey (USGS) and issued in the following circulars: *MacKichan and Kammerer* [1961], *Murray* [1968], *Murray and Reeves* [1972, 1977], and *Solley et al.* [1983, 1988, 1993, 1998]. These USGS reports, referred to below as the USGS circulars, estimate water use for states and water resource regions (WRRs) (defined by the *Water Resources Council* [1978]) and represent the only consistent effort to periodically document water use for the entire nation. The circulars cover in-stream use at hydroelectric plants, withdrawals to off-stream users, and consumptive use. They report estimated water use from three principal sources: groundwater, fresh surface water, and saline water.

This study focuses on freshwater withdrawals from the combination of groundwater and surface water sources. Water use is summarized herein for the United States as a whole and for six aggregated regions encompassing the contiguous 48 states in order to capture major regional differences. The aggregated regions (Figure 1) are groups of WRRs characterized by relatively homogenous precipitation, climate, geography, and water use characteristics, though they unavoidably each contain areas of considerable heterogeneity in at least some variables. (A more detailed breakdown for the nation's 20 WRRs is presented by *Brown* [1999]).

The USGS has improved its water use data gathering procedures over the years in part by adopting more detailed water use categories beginning with the 1985 circular. To obtain a minimum number of consistent categories for the entire 1960–1995 period, the finer distinctions introduced in 1985 were not used. Further, self-supplies (water withdrawn by the user) and public supplies (water delivered by a municipality or water company) were combined, as the source of supply was not an important distinction in this study; the sum is called a "withdrawal" herein. Thus the following categories were chosen: (1)

Table 1. Factors Used to Project Water Withdrawals

Water Use Category	Factor
Livestock	population withdrawal per person
Domestic and public	population withdrawal per person
Industrial and commercial	population income per person withdrawal per dollar of income
Thermoelectric	population total kilowatt-hours per person freshwater thermoelectric kilowatt hours per total kilowatt-hours freshwater thermoelectric withdrawal per kilowatt-hour
Irrigation	acres irrigated withdrawal per acre

One acre equals 4047 m^2.

livestock (self-supplied), (2) domestic and public (publicly supplied and self-supplied), (3) industrial and commercial (publicly supplied and self-supplied) and mining (self-supplied), (4) thermoelectric power (publicly supplied and self-supplied), and (5) irrigation (self-supplied). The "public" in "domestic and public" refers to use in government offices, public parks, and fire fighting and to losses in the public supply distribution system.

Table 1 lists the factors used to project withdrawals for the five categories of water use. Some of these factors represent water use efficiencies, which were computed using the USGS withdrawal data and data on water use determinants. A ratio of the determinant to its respective quantity of water withdrawn (e.g., domestic withdrawal per person) was computed for each category of use. Total population was used as the determinant of livestock and domestic water use and as a factor in estimating future withdrawals for industrial and commercial and thermoelectric water uses. Historical population data were taken from the *Bureau of the Census* [1992] for the years 1960–1990 with the exception of the estimate for 1965, which was obtained from the *Bureau of Economic Analysis* [1992]. Population projections through 2040 for the United States as a whole were obtained from the *Bureau of the Census* [1996]. These projections were disaggregated to the state level using projected future proportions from the *Bureau of Economic Analysis* [1995] and then disaggregated to the county level based on the distribution of state population to counties in 1990. The determinant of industrial and commercial water use was personal income; historical data and projections for per capita income were obtained from the *Bureau of Economic Analysis* [1992, 1993]. County-level historical data and projections on population and income were aggregated to WRRs using the county allocations of the Water Resources Council's Assessment Subareas [*Water Resources Council*, 1978]. Electricity production was used as the basic determinant of water withdrawals for thermoelectric plants; historical data (beginning in 1985) were taken from the USGS water use circulars. Total irrigated acres was used as the determinant for irrigation water use; historical data were obtained from the USGS circulars. Factors and withdrawal estimates were computed at the WRR level; estimates were then combined to represent aggregated regions or the entire United States.

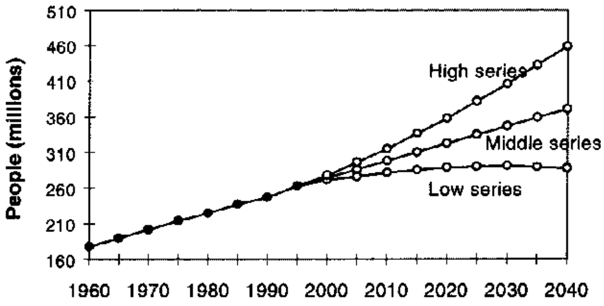

Figure 2. Census Bureau's U.S. population projections.

An important limitation of this approach is that the USGS water withdrawal estimates were sometimes based on assumed relations with other, more easily measured variables, such as population or irrigated acres, rather than on actual measures of water diversion or delivery. The degree of reliance on assumed relations of withdrawal to other variables varied by water use category, by USGS state office, and by year. Any such reliance precludes independent efforts using the USGS data to discover what factors affected water use. Thus only to the extent that the assumed relations were accurately specified do the USGS data provide a basis for describing the relations of past use to factors affecting that use and for projecting future water use.

Except for population and per capita income, future levels of all variables used to project water use were estimated especially for this study based on annual rates of change of the variables of interest. The future rates of change were chosen to extend past trends, which in most cases have been nonlinear, with the rate of change diminishing in recent years. These assumed rates of future change do not, it should be noted, reflect a detailed model, economic or otherwise. Detailed models were not used because of the judgment that our knowledge of the processes affecting the various water uses, especially at the large scale of this assessment, does not warrant or adequately support such models. Rather, the projections rely on the method of extrapolation (see *Wilmoth* [1998] for a defense of extrapolation in the absence of detailed knowledge of the underlying mechanisms affecting change) and were chosen to maintain continuity of the trend, as will be apparent in subsequent figures.

Several alternatives were available (e.g., quadratic or log functions) for specifying the nonlinear trends in factors affecting water use. The method chosen proved to be sufficiently flexible to cover all cases. Future levels of factors affecting water use were specified by applying an annual rate of change (i) to the quantity (Q) of the prior time period. Quantity for year n was computed as: $Q_n = Q_{n-t}\,(1 + i_n)^t$, where t gives time period length in years and $i_n = i_{n-t}\,(1 + d)^t$, where d is an annual decay of the rate of change chosen to maintain continuity of the prior trend. Rates i and d were selected separately for each water use factor and geographic area. Rate of change (i) was positive, negative, or nil depending on the prior trend. Decay (d) was always negative in keeping with the general observation of diminishing rate of change.

The Census Bureau projects three levels of future population (the high, middle, and low series in Figure 2) based on assumptions about life expectancy, fertility, and immigration (for details, see *Bureau of the Census* [1996]). The middle series projections show U.S. population increasing at annual rates of 1.0% during the 1990s, 0.8% from 2000 to 2010, and by about

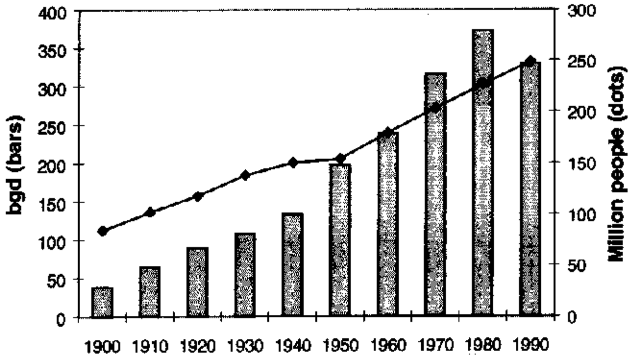

Figure 3. U.S. water withdrawal and population from 1900–1990.

0.7% thereafter, producing an overall rise from 263 million in 1995 to 370 million in 2040 (a 41% increase). The low and high series project total population to increase from 1995 to 2040 by 9% and 74%, respectively. The Census Bureau does not present confidence limits about these different estimates.

3. Past U.S. Water Withdrawals

Growth in total U.S. water withdrawals during the twentieth century has, until recently, consistently outpaced population growth (Figure 3) [*Bureau of the Census* [1976]; *Council on Environmental Quality* [1989]; USGS circulars]. The changes in these two variables fall into three distinct periods: before the Second World War, after that war through 1980, and since 1980. From 1900 to 1940, population increased by roughly 1.7 million persons per year, while withdrawals increased by about 2.4 billion gallons per day (BGD) (1 gallon equals 3.8 L) per year. From 1950 to 1980, population increased by about 2.4 million persons per year, while withdrawals increased by about 5.7 BGD per year. After 1980, total withdrawals dropped (and then leveled off, as seen below), but population continued to rise. The full change from 1900 to 1990 translates into an annual increase of 1.2% for population and 2.4% for withdrawal.

Figure 3 shows a striking change in 1990, when total withdrawals dropped for the first time in the century. Figure 4, which presents withdrawals at 5-year intervals since 1960 based on the USGS water use circulars, shows that the drop first occurred in 1985 and that it is attributable to the top three categories: irrigation, thermoelectric use, and industrial and commercial use. The drop in 1985 was due partly to (1) above average rainfall that year, which lessened the need for irrigation withdrawals, (2) an economic slowdown and lower commodity prices, (3) higher groundwater pumping costs as lifts had continued to increase, and (4) improved efficiency in water use [*Solley et al.*, 1988]. However, the drop in 1985 was also partially attributable to the improved process for amassing the water use data that was initiated by the USGS for the 1985 report, indicating that earlier estimates were probably too high [*Solley et al.* 1988; *Brown*, 1999]. This possibility highlights the importance of focusing on long-term trends rather than short-term shifts when using the water use data.

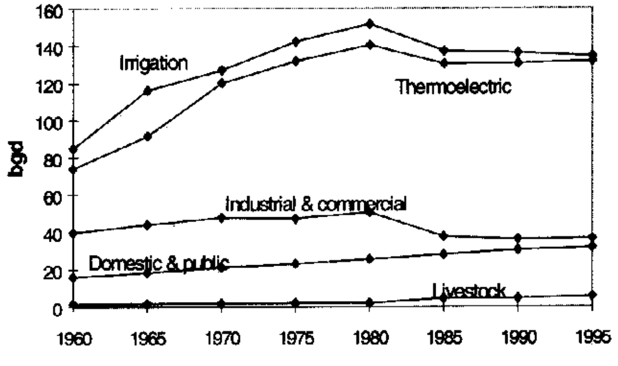

Figure 4. U.S. water withdrawals by use category from 1960–1995.

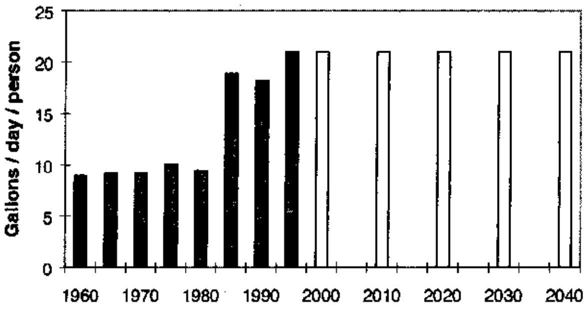

Figure 5. Livestock water withdrawal per capita.

4. Past and Projected Water Use Efficiencies

Subsections 4.1–4.5 discuss trends in withdrawals and factors affecting those withdrawals for the five water use categories shown in Figure 4, beginning with the smallest use category, livestock, and ending with the largest, irrigation. In Figures 5–13, past withdrawals are depicted by shaded bars, and future withdrawals are depicted by open bars; dark shaded dots show past levels of related factors, and light shaded dots are used for future levels.

4.1. Livestock

The USGS's livestock water use category consisted of use by terrestrial animals (or "stock," principally cattle, hogs, sheep, and poultry) until 1985 when "animal specialties" (consisting largely of aquaculture or fish farming) were moved from the industrial to the livestock category. Total livestock withdrawals for the United States gradually increased from 1.6 BGD in 1960 to 2.1 BGD in 1980 in response to increasing animal numbers and then more than doubled in 1985 (to 4.5 BGD) when animal specialties were added (Figure 4).

Water use by terrestrial animals has been estimated by the USGS largely based on numbers of animals served, with different animal species assigned their respective average water requirements. Use of water at fish farms was typically estimated based on pond area and estimates of evaporation and seepage. Estimates of future stock numbers and pond areas were not available for projecting future livestock water use. Human population was used as the determinant based on the assumption that consumer tastes for meat, egg, and fish consumption will remain constant.

Stock withdrawal per person, in fact, remained quite constant from 1960 to 1995, ranging between 9 and 10 gallons d^{-1} (Figure 5 shows stock use alone for 1960–1980). Adding water use for animal specialties raised withdrawal per person from 18 to 21 gallons d^{-1} since 1985 (Figure 5). The 3-gallon $person^{-1}$ d^{-1}

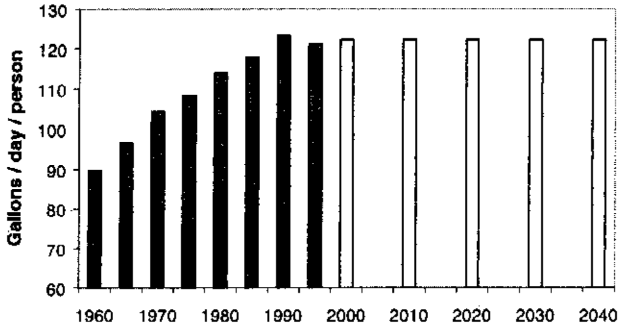

Figure 6. Domestic and public water withdrawal per capita.

change from 1990 to 1995 is totally attributable to increased water use by aquaculture, suggesting that use of water per person in aquaculture may be growing, but the record for this use is too short to support trend extensions. Thus future per capita livestock withdrawals were assumed to remain constant at the 1995 level of 21 gallons d^{-1} (Figure 5).

4.2. Domestic and Public Use

Total U.S. withdrawals for domestic and public water use (public uses and losses are about 15% of total domestic and public withdrawals) rose from 16 BGD in 1960 to 32 BGD in 1995 (Figure 4). The rise in domestic and public withdrawal was primarily caused by population growth, but per capita domestic and public withdrawal also steadily increased from 89 gallons d^{-1} in 1960 to 122 in 1990 (Figure 6). This increasing per capita water use may be largely attributable to a decrease in average household size [*Schefter*, 1990]. People per household (i.e., per occupied housing unit) decreased from 3.4 in 1960 to 2.7 in 1995. Because a certain minimum level of water use per household, especially for lawn and garden watering, is largely unrelated to household size, per capita use rises as household size drops.

Other factors probably contributing to the increase in water use per capita include the conversion of older or rural households to complete plumbing and an increase in use of water-using amenities such as dishwashers, washing machines, swimming pools, and lawn sprinkler systems. These changes are consistent with the increasing real incomes and decreasing real domestic water prices that were experienced in many areas of the United States over the past 3 decades [*Schefter*, 1990].

The consistent growth in per capita domestic and public withdrawals observed since at least 1960 may have finally ended, for those withdrawals dropped from 122 gallons d^{-1} in 1990 to 120 in 1995 (Figure 6). This change may be the result of conservation programs and the use of more efficient plumbing fixtures in newer homes and renovations, in part pursuant to water use provisions of the Energy Policy Act of 1992 (public law 102-486), plus the dwindling of the drop in household size [*Brown*, 1999]. It is too soon to know for sure whether this change in per capita use will persist.

Future domestic and public withdrawals were projected as population × (withdrawal person^{-1}). The projection hinges on the recent shift in per capita use. This shift might be ignored as too recent and too small to indicate a major change in the prior, very consistent trend. However, the factors listed above (the end of the drop in household size, the completion of conversion to modern plumbing, and the growing impact of conservation measures) suggest that a significant trend change may be occurring and that additional decreases may be in store. Given this conundrum, it is assumed here that future per capita withdrawal will remain constant at 121 gallons d^{-1}, equal to the midpoint between the 1990 and 1995 levels (Figure 6).

4.3. Industrial and Commercial Use

Total U.S. industrial and commercial withdrawals show a gradual rise from 1960 to 1980 and then the sharp decrease in 1985 discussed in section 3 (Figure 4). Only about 2.3 of the 13 BGD drop from 1980 to 1985 is attributable to moving animal specialties to the livestock water use category. Since 1985, total withdrawals have remained at about 36 BGD.

Because of the great variety of outputs of the industrial and commercial sectors, relating water use to units of physical output was unrealistic. Instead, an economic measure of total output, personal income, was used. Withdrawal per dollar of total real personal income in the United States has declined steadily from 24 gallons in 1960 to 7 gallons in 1995 (bars in Figure 7). The drop in withdrawal per dollar of income is largely attributable to changes in the type and quantity of industrial and commercial outputs, such as a shift from water intensive manufacturing and other heavy industrial activity to

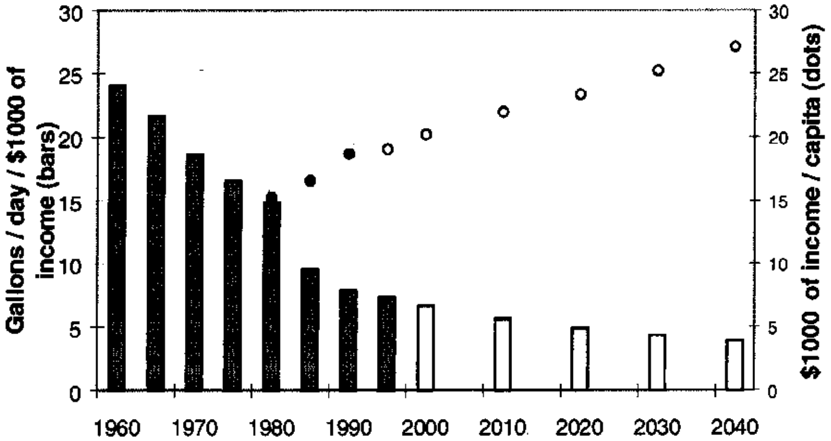

Figure 7. Industrial and commercial water withdrawal per dollar and income per capita (income in 1990 dollars).

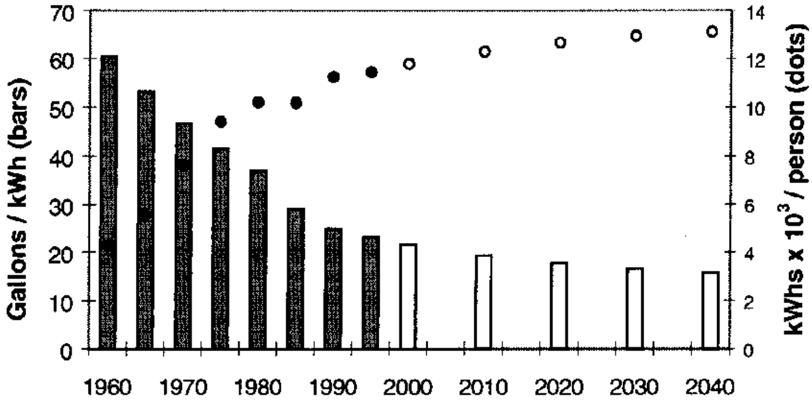

Figure 8. Total energy production per person and thermoelectric freshwater withdrawal per kilowatt-hour.

service-oriented businesses, and to enhanced efficiency of water use. Efficiency improved in response to such factors as environmental pollution legislation (e.g., the Clean Water Act of 1972 and its amendments), which regulated discharges and thereby encouraged reductions in withdrawals (made possible by modifying production process and recycling withdrawn water), and technological advances facilitating recycling [*David*, 1990]. The most recent data show that the rate of decrease in water withdrawal per dollar of income has slackened somewhat (Figure 7).

Future industrial and commercial withdrawals were projected as population × (dollars of income per capita) × (withdrawal per dollar of income). The *Bureau of Economic Analysis (BEA)* [1992, 1995] projects per capita income, in 1990 dollars, to increase from \$19,001 in 1995 to \$27,103 in 2040, which is equivalent to a growth rate of about 0.8% per year (dots in Figure 7). Withdrawal per \$1000 of income, which dropped at annual rates of 2.5% during the 1960s, 2.3% during the 1970s, and 6.1% during the 1980s (but by only 1% from 1990 to 1995), was assumed to drop at a gradually decreasing rate of from 2% to 1% per year over the 1995–2040 period. Given this assumption, withdrawal per \$1000 of income drops from 7.4 gallons in 1995 to 3.9 gallons in 2040 (bars in Figure 7).

4.4. Thermoelectric Use

Water is used at thermoelectric power plants (mainly fossil fuel and nuclear plants) principally for condenser and reactor cooling. Total freshwater withdrawals increased steadily through 1980, declined substantially in 1985 as mentioned in section 3, and have increased slightly since then (Figure 4). Withdrawals of saline water, which equal roughly 30% of recent total water withdrawals at thermoelectric plants and are not shown in Figure 4, have remained roughly constant since 1975.

In contrast to the recent leveling off of total withdrawals, production of electricity at thermoelectric plants in the United States has risen consistently over the past 35 years, rising from 447×10^9 kWh in 1960 to 2081×10^9 in 1995. Consequently, freshwater withdrawal per kilowatt-hour produced has declined steadily and in 1995 was only 42% of its 1960 value (bars Figure 8). The improved efficiency of water use has occurred partly because of greater reuse of withdrawn water; this reuse is indicated by the change in consumptive use, which, though still a small fraction of withdrawal, increased by a factor of 14 from 1960 to 1995. The latest data indicate a lessening in the rate of decrease in withdrawal per kilowatt-hour (Figure 8).

Withdrawals at thermoelectric plants were projected as population × (total kilowatt-hours per person) × (freshwater thermoelectric kilowatt-hours per total kilowatt-hours) × (freshwater withdrawal per freshwater thermoelectric kilowatt-hour). Total (thermoelectric plus hydroelectric) energy use per person rose from about 4200 kWh per year in 1960 to about 11,400 kWh in 1995 (dots in Figure 8). In percentage terms, total per capita energy use rose at annual rates of 6% during the 1960s, 3% during the 1970s, and 1% during the 1980s (but by only 0.4% from 1990 to 1995). In keeping with this decreasing trend, future total energy use was assumed to increase by an annual rate decreasing from 0.6% to 0.14% over the period 1995–2040 (Figure 8), bringing total per capita energy use to about 13,100 kWhs per year in 2040. This rate of increase reflects a rough balance between development of still more energy-using conveniences, which would call for greater use per person, and improvements in energy efficiency of all such conveniences, which would call for less.

Further, it was assumed that generation at hydroelectric plants will remain constant at the 1995 level (it has been quite stable since 1975), so that all increases in production occur at thermoelectric plants, and that the allocation of thermoelectric energy production between freshwater and saltwater plants will remain constant at the 1995 level (70% at freshwater plants for the United States as a whole). Given these assumptions, use of energy generated at freshwater thermoelectric plants, which increased from 2493 kWhs person^{-1} y^{-1} in 1960 to 7917 in 1995, was assumed to reach 10,061 kWhs person^{-1} y^{-1} in 2040.

Water use per kilowatt-hour produced at thermoelectric plants decreased at annual rates of 2.7% from 1960 to 1985 and 2.0% from 1985 to 1995. In keeping with this apparent leveling off of the rate of decrease, future water use per kilowatt-hour was assumed to decrease by 1.3–0.6% y^{-1} over the period from 1995 to 2040. Given this rate of decrease, water use per kilowatt-hour produced at freshwater thermoelectric plants, which decreased from 60 gallons kWh^{-1} in 1960 to 23 in 1995, reaches 16 gallons kWh^{-1} in 2040 (bars in Figure 8).

4.5. Irrigation

U.S. withdrawals for irrigation steadily increased from 1960 to 1980 and then declined in 1985, with additional smaller decreases since then (Figure 4). The decreases since 1985 are

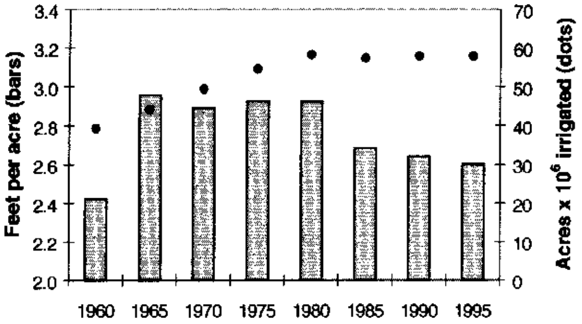

Figure 9. U.S. irrigation water withdrawal depth and acres irrigated.

not a simple function of irrigated acreage changes, as overall irrigated acreage rose from 57.2 million acres (1 acre = 4047 m^2) in 1985 to 57.9 million acres in 1995 (dots in Figure 9).

However, a closer look reveals a geographical difference in irrigated acreage trends. The arid and semiarid western states, where the vast majority of irrigation occurs, are experiencing a decrease in irrigated acreage that began in the early 1980s as farmers sold some of their land or water to cities, industries, and rural domestic users and as pumping costs and crop prices caused marginal lands to be removed from irrigation. Meanwhile, farmers in eastern states have been relying more on irrigation water to supplement precipitation during dry times in order to reduce variability in yields and product quality [*Moore et al.*, 1990]. This phenomenon is depicted in Figure 10, where the east is characterized by WRRs 1–9 and the west is characterized by WRRs 10–18. The drop in irrigated acreage in western regions, which tend to use relatively large amounts of water per acre, and the rise in irrigated acreage in eastern regions, which uses relatively less water per acre, is partly responsible for the nationwide drop in water application per acre that began in 1985 (bars in Figure 9).

In addition to the acreage shift the recent downward trend in national withdrawal per acre (Figure 9) reflects a reduction in water application. As seen in Figure 11, application rates dropped in both the east and the west from 1980 to 1985 and have continued to drop in the west. The portion of withdrawal that is consumptively used is one indication of irrigation efficiency; improved methods withdraw less water for a given amount of evapotranspiration. Consumptive use increased from 47% to 59% of total withdrawal in the west from 1985 to 1995. If these estimates are accurate (note that measures of consumptive use rely on a good deal of educated judgment), they partially explain the drop in withdrawal per acre. Improved irrigation efficiency may be a response to such factors as the waning of the era of publicly funded dam and canal construction, higher prices for water from publicly funded projects, increasing groundwater pumping lifts, and improved irrigation technology [*Moore et al.*, 1990].

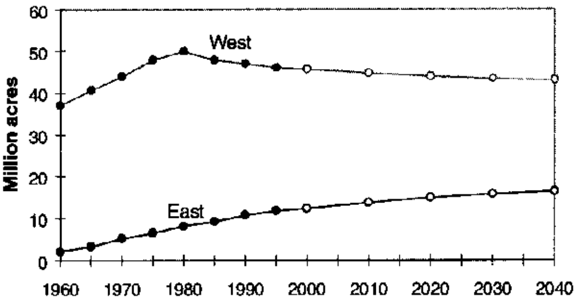

Figure 10. Irrigated acreage.

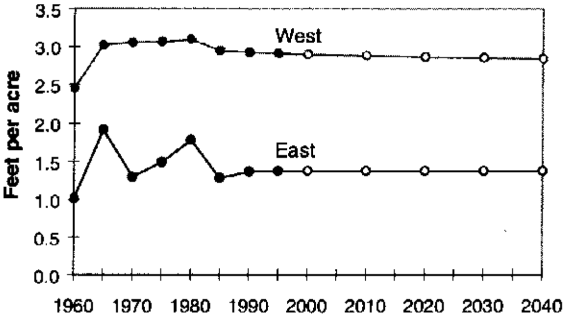

Figure 11. Depth of irrigation water withdrawal.

Projecting irrigation water use is difficult because so many factors affect agricultural acreage and withdrawal per acre. Irrigation is a lower-valued use of water at the margin than most other uses (most of the recent water trades in the western states, for example, have been from agriculture to municipal and industrial uses [*Saliba*, 1987]), so that withdrawals for irrigation are partially a function of water use in the more highly valued uses. In addition, irrigation water use is a complicated function of population, as increases in population both increase demand for crops and, via urban expansion, decrease availability of irrigable land. Further major factors affecting irrigation include energy prices (via their effect on pumping costs), irrigation technologies, international markets for agricultural crops, federal agricultural policies, in-stream flow concerns, and precipitation variations.

In light of the difficulty of accounting for all these factors a simple approach was adopted for estimating future irrigation withdrawals, which sets withdrawal equal to irrigated acreage × (withdrawal per acre), with future acreage and withdrawal per acre estimated by extrapolating past trends. Acreage was projected at the WRR level and is expected to increase in nine WRRs (including all but one of the nine eastern WRRs), decrease in seven, and remain constant in four. Figure 10 summarizes the projected acreage totals for the east and west. For the entire United States, irrigated acreage is projected to increase from 57.9 million acres in 1995 to 62.4 million in 2040.

Withdrawal per acre can vary considerably from year to year at the WRR level because of weather. Thus time trends of withdrawal per acre at the WRR level are often erratic. To avoid this localized phenomenon, trends in withdrawal per acre were investigated for the eastern and western United States. In the west, withdrawal per acre, which fell at annual rates of 1% from 1980 to 1985 and 0.1% from 1985 to 1995, was assumed to continue falling at a lesser rate of from 0.08% to 0.04% for the period 1995 to 2040. Given these rates, withdrawal per acre in the west, which dropped from 3.1 feet (1 foot equals 0.3048 m) in 1980 to 2.91 feet in 1995, drops to 2.84 feet by 2040 (Figure 11). In the east, withdrawal per acre was assumed to remain constant, in keeping with the recent trend. These rates of decrease in withdrawal per acre were applied to beginning rates in each WRR set equal to the mean for the years 1985, 1990, and 1995. For example, the results of this procedure for two WRRs, the South Atlantic-Gulf and Pacific

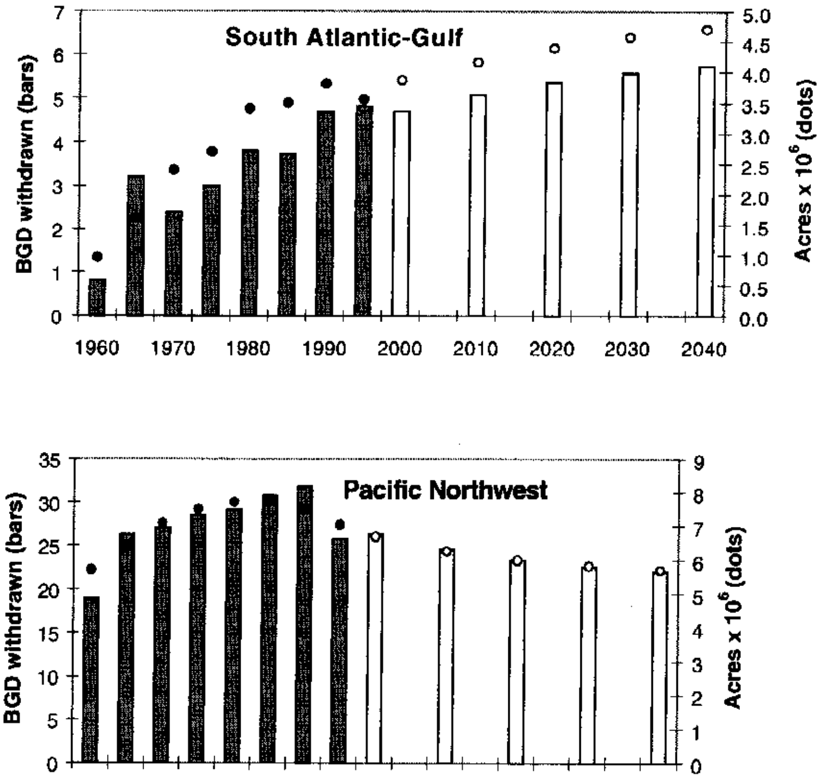

Figure 12. Water withdrawal and irrigated acres in two WRRs.

Northwest, are seen in Figure 12 (see *Brown* [1999] for details on all 20 WRRs).

5. Projected Water Withdrawals

Projections are presented first for the entire United States and then for the six aggregated regions.

5.1. National Withdrawals

Figure 13 depicts projections for all five water use categories at the national level using the Census Bureau's middle series population projections. Total livestock withdrawal in the United States is projected to rise from 5.5 BGD in 1995 to 7.7 BGD in 2040 in a direct response to population growth. Domestic and public withdrawals are projected to increase from 32 BGD in 1995 to 45 BGD in 2040, again in response to population growth. Industrial and commercial withdrawals are projected to rise only slightly from 37 BGD in 1995 to 39 BGD in 2040, a 5% increase; the decreasing withdrawal per dollar largely compensates for the continued increases in population and per capita income. Freshwater withdrawals at thermoelectric plants are projected to rise from 132 BGD in 1995 to 143 BGD in 2040, an 9% increase; the decreasing withdrawal per kilowatt-hour only partially compensates for increases in freshwater thermoelectric production (from 2.1 × 10^{12} kWh in 1995 to 3.5 × 10^{12} kWh in 2040) required to accommodate the growing population and per capita energy use. Finally, total irrigation withdrawals decrease slightly from 134 BGD in 1995 to 130 BGD in 2040 in response to projected changes in irrigated acreage and withdrawal per acre.

The graph at the bottom of Figure 13 shows that total withdrawals across all uses are projected to increase by 7% (24 BGD) from 1995 to 2040. The largest increases are in the domestic and public (13 BGD) and thermoelectric (11 BGD) sectors. The livestock and industrial and commercial sectors each contribute another 2 BGD to the increase, and irrigation withdrawals decrease by 4 BGD.

Holding the overall increase below 10% of total 1995 withdrawals, in spite of the 41% increase in population, is largely attributable to the improving efficiencies projected for the industrial and commercial and thermoelectric sectors and for irrigation in the west and to the drop in irrigated acreage in the west.

Table 2 compares the results using the middle population series with results using the low- and high-population series projections. In contrast to the 7% increase in total withdrawals from 1995 to 2040 with the middle series, the low and high series yield changes in withdrawal of −8% and 24%, respectively.

5.2. Withdrawals for Aggregated Regions

Table 3 summarizes the projections for the aggregated regions in terms of the change from 1995 to 2040, assuming the Census Bureau's middle-series population projections and the irrigated acreage changes as listed, which were computed from the respective WRR amounts. All six regions show substantial increases in livestock and domestic and public withdrawals in keeping with the expected increases in population in all regions. Industrial and commercial withdrawals are projected to decrease slightly in the northeast and north central regions and to increase moderately in the other four regions. Regions with the greatest population increases experience the greatest increases in industrial and commercial withdrawal.

Thermoelectric withdrawals increase in all six regions. The

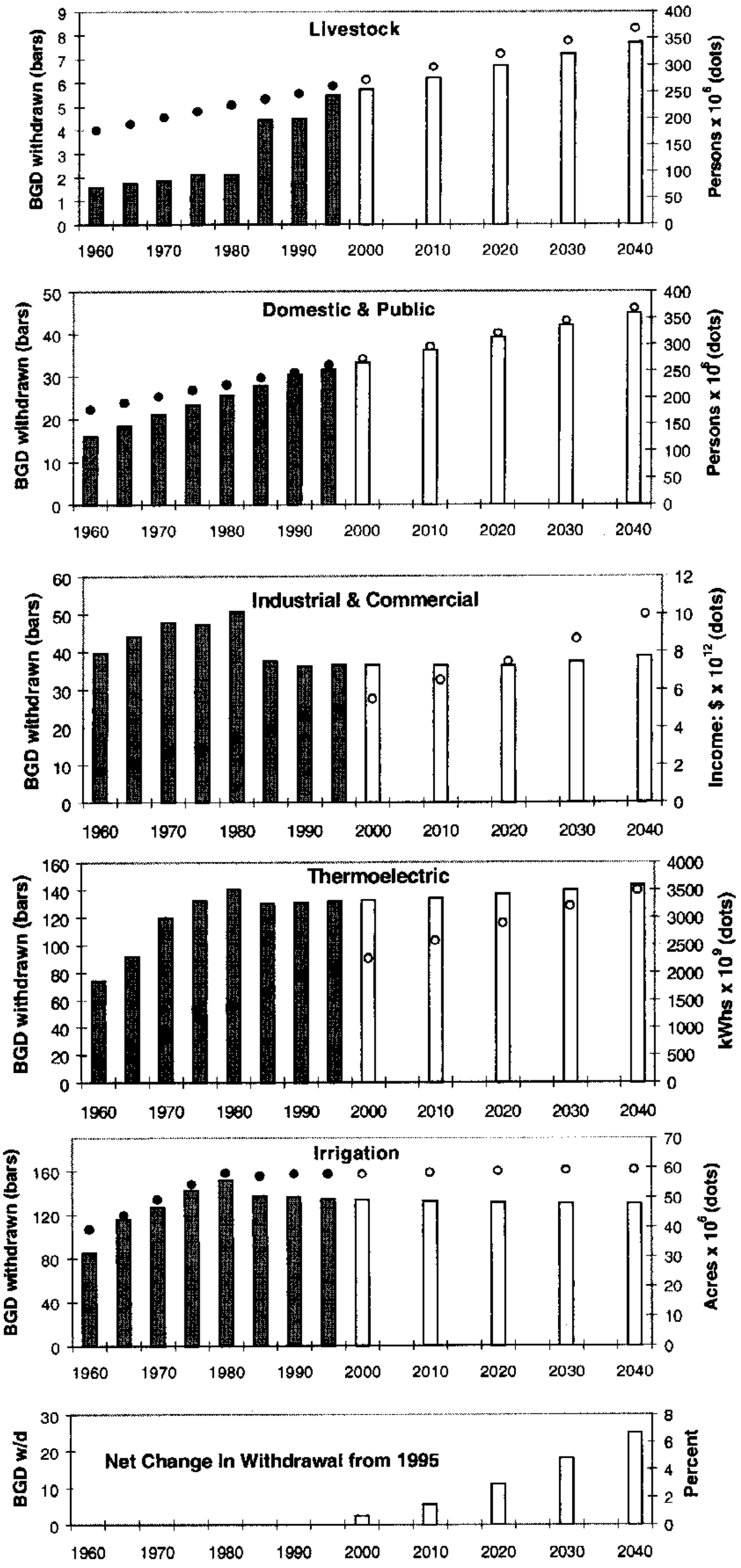

Figure 13. Projected U.S. water withdrawals.

Table 2. National Withdrawal Projections for Alternative Population Series, Expressed as Change From 1995 to 2040

	Low Series	Middle Series	High Series
Population, millions	24 (9)	107 (41)	195 (74)
Withdrawal, BGD			
Livestock	1 (9)	2 (41)	4 (75)
Domestic and public	3 (10)	13 (42)	24 (76)
Industrial and commercial	−6 (−17)	2 (6)	12 (32)
Thermoelectric	−22 (−17)	11 (9)	48 (36)
Irrigation	−4 (−3)	−4 (−3)	−4 (−3)
Total	−29 (−8)	24 (7)	83 (24)

Percent change from 1995 to 2040 is indicated in parentheses.
BGD is billion gallons per day.

percentage increases are small in the two regions with the smallest percentage population increase (the northeast and north central regions) and are moderate in the southeast and Great Plains (Table 3). The two western regions are expected to experience the greatest percentage increases in thermoelectric withdrawal but small actual increases. The western regions currently produce much of their electricity at hydroelectric plants. With the assumption of no future increases at hydroelectric plants, all of the expected increases in electricity production must be supplied at thermoelectric plants. In the two western regions the required increase in production at thermoelectric plants cancels or overwhelms the increase in water use efficiency, resulting in withdrawal increases of 33% and 120%, respectively. Finally, irrigation withdrawals differ among regions, reflecting mainly the projected changes in irrigated acreage.

The net change in total withdrawal among the six aggregated regions varies from 0 to 27%. The two eastern regions are projected to experience the greatest percentage increases, 9% in the northeast and 27% in the southeast. Most of the increase in the northeast is attributable to domestic and public use, whereas in the southeast the domestic and public, thermoelectric, and agricultural sectors all contribute substantially to the total increase. The increases in total withdrawal in the north central and Great Plains and Texas Gulf regions (of 4% and 2%, respectively) are mostly attributable to domestic and public and thermoelectric uses. The 5% increase in the southwest region is largely attributable to domestic and public uses.

5.3. Sensitivity of Projections to Assumptions About Factors Affecting Water Use

Many kinds of sensitivity analyses are possible; only two are presented here. First, Table 4 lists the percent change, from the results presented above, in total withdrawal in year 2040 that is caused by a 10% change in a factor affecting projected water use. For example, the upper left estimate of 6.6% indicates that if future U.S. population were 10% greater than projected by the Census Bureau's middle series, total withdrawals in year 2040 would be 6.6% greater than those indicated in Figure 13. For the United States as a whole, total withdrawals are most sensitive to percent population changes, next most sensitive to percent changes in factors affecting thermoelectric water use, and least sensitive to percent changes in withdrawal per dollar of income. Differences among aggregated regions in sensitivity to changes in factors affecting water use reflect the relative shares of total withdrawal going to different water uses (Table 4).

Second, Table 5 lists use rates that would be required to keep year 2040 withdrawals of the respective water uses at their 1995 levels, with other assumptions about future water use factors (e.g., middle population series projections, *BEA* [1995] income projections, and allocation of electricity production between hydroelectric and thermoelectric options) unchanged. For example, domestic and public withdrawals, which were projected to remain constant at 121 gallons d^{-1} person^{-1}, would have to decrease to 86 gallons d^{-1} person^{-1} in 2040 (a

Table 3. Change in Population, Irrigated Acreage, and Withdrawal From 1995 to 2040 for Aggregated Regions, Assuming the Census Bureau's Middle Population Projection Series

	Northeast	Southeast	North Central	Great Plains and Texas Gulf	Southwest	Pacific Coast
Population, millions	17 (31)	25 (51)	20 (30)	14 (41)	7 (64)	22 (52)
Irrigated acres, millions	0.1 (12)	3.7 (40)	0.8 (40)	−1.4 (−6)	0.2 (4)	−1.7 (−11)
Withdrawal, BGD						
Livestock	0.0 (31)	0.8 (51)	0.1 (30)	0.4 (41)	0.1 (64)	1.0 (52)
Domestic and public	1.9 (31)	3.0 (51)	1.9 (30)	2.1 (41)	1.2 (64)	3.1 (52)
Industrial and commercial	−0.2 (−5)	1.3 (14)	−0.5 (−4)	0.3 (8)	0.3 (26)	0.6 (12)
Thermoelectric	0.5 (3)	6.2 (20)	1.2 (2)	2.4 (11)	0.1 (33)	0.7 (120)
Irrigation	−0.0 (−5)	5.4 (41)	0.4 (35)	−3.8 (−10)	−0.3 (−1)	−5.7 (−10)
Total	2.2 (9)	16.6 (27)	3.2 (4)	1.3 (2)	1.5 (5)	−0.2 (0)

Percent change from 1995 to 2040 is indicated in parentheses.

Table 4. Percent Change in Total Withdrawal in 2040 Caused by a 10% Increase in Factors Affecting Water Use

Region	Factor					
	Population	Withdrawal per Person	Withdrawal per Dollar of PCI	Withdrawal per Kilowatt-Hour	Kilowatt-Hours per Person	Acres Irrigated
United States	6.6	1.2	1.1	3.9	4.1	3.6
Aggregated regions						
Northeast	10.0	2.9	1.4	5.4	5.5	0.2
Southeast	7.8	1.1	1.4	4.8	5.0	2.4
North central	10.0	1.0	1.4	7.4	7.6	0.2
Great Plains and Texas Gulf	5.1	1.0	0.6	3.2	3.3	5.0
Southwest	1.8	1.1	0.5	0.1	0.1	8.2
Pacific coast	2.9	1.3	0.8	0.2	0.3	7.2

PCI is per capita income.

29% drop) to keep total domestic and public withdrawal at the 1995 level (of 32 BGD). As seen in the right-hand column of Table 5, keeping withdrawals at their 1995 levels would require a much smaller percentage change in efficiency of water use in the industrial and commercial and thermoelectric sectors than in the domestic and public or livestock sectors.

6. Comparison of Projections

Table 6 presents a brief comparison of U.S. water withdrawal projections. Given that actual withdrawal in 1995 was 340 BGD, this study's projection of 341 BGD for year 2000 must be reasonably accurate. As Table 6 shows, most early projections grossly overestimated year 2000 withdrawals. The *Water Resource Council*'s [1978] projection, however, is a notable exception, as it actually underestimated year 2000 withdrawal. This low estimate resulted from underestimating population and from overly optimistic projected decreases in manufacturing, thermoelectric, and irrigation withdrawals, but it was a far more accurate estimate than other early attempts that ignored or downplayed future improvements in the efficiency of water use.

Also shown in Table 6 are *Guldin*'s [1989] projections for years 2020 and 2040. Guldin reached considerably higher withdrawal projections than the current study despite his lower population projection (e.g., Guldin assumed a year 2040 U.S. population of 333 million versus this study's 370 million). The different projections of the two studies are attributable mainly to different approaches for considering water use efficiency; Guldin assumed no further gains in water use efficiency beyond those already achieved by 1985, whereas this study extrapolated trends in efficiency gains into the future.

7. Summary and Caveats

Improvements in the efficiency of water use, especially in the industrial and commercial and thermoelectric sectors but also recently in domestic and public and irrigation water use, have kept U.S. withdrawals well below most past projections. These improvements in water use efficiency are a response to such changes as plumbing fixture ordinances, price increases, reductions in government subsidies, and environmental pollution regulations. If these efficiency trends continue, total withdrawals in the year 2040 are projected to be only 7% above those in 1995, despite a projected 41% increase in population. However, such withdrawal increases will decrease in-stream flows also desired by the growing population, leading to greater environmental conflicts.

The approach employed here to project water use relied on extending past trends in a few basic water use factors. Those factors (e.g., population, withdrawal per household, kilowatt-hours per person, and irrigated acres), plus other factors affecting water use that were not analyzed (e.g., changes in hydropower capacity and effects of international demand for grain on irrigated acres), are subject to public policy. For example, population is subject to immigration policy; domestic withdrawal per person is subject to water prices as well as regulations affecting the efficiency of water-using appliances;

Table 5. Required Levels of Selected Water Use Factors to Keep Year 2040 Withdrawal for Respective Water Use Categories at the 1995 Level for the United States as a Whole

Water Use Category	Factor	Level of Factor			
			Year 2040		
		Year 1995	Best Guess	Requirement	Percent Change
Livestock	gallons d^{-1} person^{-1}	21	21	15	−29
Domestic and public	gallons d^{-1} person^{-1}	122	121	86	−29
Industrial and commercial	gallons $\$1000^{-1}$	7.35	3.89	3.63	−7
Thermoelectric	total kWh y^{-1} person^{-1}	11775	13125	12123	−8
Thermoelectric	gallons kWh^{-1}	23.1	15.0	13.9	−7

Table 6. Projections of U.S. Water Withdrawals for Three Future Years Based on Medium or Best Guess Assumptions

	2000	2020	2040
Senate Select Committee on National Water Resources [1961]	888		
Water Resources Council [1968]	804	1368	
Wollman and Bonem [1971]	563	897	
National Water Commission [1973]	1000		
Water Resources Council [1978]	306		
Guldin [1989]	385	461	527
Current study	341	350	364

Values are in billion gallons per day.

and irrigated acreage is subject to a host of influences including subsidization of water supply, crop price supports, international trade policy, and regulations affecting the ease with which water trades may occur. Significant policy changes could alter water use in ways not captured by the method of extending past trends in water use efficiencies as done herein. For example, greater efforts to conserve domestic water use through pricing structures and to remove barriers to voluntary water trades could create even lower use levels than projected.

The assumptions on which the projections depend may turn out to have been optimistic. In addition, the projections apply to the average year, not to the more worrisome dry years, and to large-scale regions, not to specific locations that experience above average impacts. The considerable likelihood that, especially during dry years, the projected water use increases will not be met, or will be met only by causing serious side effects, suggests that it is only prudent of U.S. water policy makers to encourage water conservation and improvements in the efficiency of water use when such changes can be accomplished without exorbitant cost.

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