

Chapter 12. Water Resources

In this chapter, we focus on the vulnerability of U.S. fresh-water supplies considering all lands, not just forest and rangelands. We do not assess the condition of those lands or report on how much of our water supply originates on lands of different land covers or ownerships, because earlier Resources Planning Act (RPA) Assessment work addressed these topics. Regarding the source of water supply, we found that forests are the source of more than one-half of the U.S. water supply and of fully two-thirds of the water supply in the West and the South, and that national forests and grasslands alone are the source of one-half of the water supply in the Western States

(Brown et al. 2008). Because forests are also generally the source of the highest quality runoff (Brown and Binkley 1994), it is not an exaggeration to say that forests play an extremely important role in the provision of water in the United States. Regarding the current condition of watersheds with National Forest System lands, we found, among other things, that the watersheds in the Interior West are generally at lower risk of impairment than those along the West Coast, which in turn are generally at lower risk than those in the East (Brown and Froemke 2010; Brown and Froemke 2012).

RESOURCE HIGHLIGHTS

- ❖ Climate change will increase future water demands.
 - ❖ Projected water withdrawal varies considerably across regions.
 - ❖ Future water use depends most importantly on the agricultural sector.
 - ❖ U.S. water yield is projected to decrease.
 - ❖ The vulnerability of the U.S. water supply will increase.
 - ❖ Increases in vulnerability depend both on changes in water yield and on growth in water demand.
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Off-stream freshwater use in the United States increased more than 10-fold during the 20th century in response to tremendous population and economic growth. Although aggregate water withdrawal in the United States has leveled off in recent years and water use efficiency has been improving, future population and income growth may place additional demands on raw water supplies. As withdrawals increase, more water is often consumed, leaving less water in lakes, streams, and reservoirs. In addition, climate change is increasing hydrologic uncertainty and may reduce available supplies and increase demands. Taken together, these forces are making careful water management ever more important and call for a broad-scale understanding of the vulnerability of our water supply to shortage.

In assessing vulnerability, we are not attempting to show how water allocation will actually change in response to population

growth and climate change. Rather, we aim to show where and to what extent water shortages would occur if populations grew and the climate changed as projected, but water management infrastructure and allocation procedures did not change and past trends in water use rates continued into the future. In other words, we are assessing the vulnerability of water supplies to shortage and showing where and when adaptation to changing circumstances is likely to be most essential.

Many different aspects of water resources could have been covered in this RPA Assessment, including changes in water quality, flooding, dwindling groundwater supplies, and instream flow issues. Our focus on shortages of renewable water supply should not be taken as an indication that other water-related challenges are less important.

Assessing Vulnerability to Water Supply Shortage

Vulnerability has been much discussed recently (e.g., Fowler et al. 2003; Füssel 2007; Gleick 1990; Vörösmarty et al. 2000). Some definitions emphasize not only the likelihood of problems, but also the ability to cope with those problems (Schneider et al. 2007; Wilby and Miller 2009). Given the broad geographic and temporal scope of this assessment, a limited definition of vulnerability was adopted, one that focuses on the consequences of projected trends if adaptation (e.g., additional conservation measures, water trading, and reservoir storage capacity) were not forthcoming. We estimate the vulnerability of renewable freshwater supply to shortage in the conterminous United States from now to 2060 in light of projected socioeconomic and climate changes.

Vulnerability is defined here as the probability of shortage, equal to the probability that the quantity of water demanded exceeds the available supply. “Current” vulnerability is evaluated during the 20-year period from 1986 to 2005. Future vulnerability is estimated for three 20-year periods centered at 2020, 2040, and 2060. For a detailed report on the water supply and demand projections and the assessment of future vulnerability of freshwater supplies to shortage, see Foti et al. (in press).

Vulnerability is estimated for the 98 assessment subregions (ASRs) of the conterminous United States. The ASRs and the water resource regions (WRRs) to which they belong are shown in figure 103. The ASRs are nearly identical to those defined by the U.S. Water Resources Council (1978) for its second national water assessment. Most of the ASRs are part of linked networks. Two or more ASRs are part of the same network when a sequence of water links, either natural (because

of upstream-to-downstream flow) or artificial (via water diversions), connects them. The ASR-based water supply system for the United States consists of three multi-ASR networks and 15 single-ASR systems (figure 104). The biggest of the three multi-ASR networks includes 69 ASRs in the Central and Western United States. The other two multi-ASR networks include, respectively, 10 ASRs in the Northeast and 4 ASRs in the Southeast. Of the 15 single-ASR systems, 8 drain to the ocean, 5 drain into Canada, and 2 are closed basins.

A hydrologic network model (Labadie et al. 1984) was used to simulate water management in each water network. The model performs year-by-year linear optimizations of water allocation in a network consisting of a system of nodes connected by links. Each link is subject to capacity constraints and is assigned a priority that reflects the operating rules of the system. Each node is a point of water storage, reservoir evaporation, and/or water diversion. The simulations provide annual values of water flows in any link, storage levels and reservoir evaporation in each ASR, and water assigned to each demand, all of which depend on both climate and the set of priorities.

Ideally, the priorities would represent all of the detailed agreements about water storage and allocation that exist across the country. Lacking information on many of those agreements, we implemented a simple set of priorities in the following order: (1) instream flow requirements, (2) trans-ASR diversions, (3) consumptive water uses, and (4) reservoir storage. These priorities recognize the importance of guaranteeing a minimal amount of water for environmental and ecosystem needs before water is diverted for other uses and enable transbasin diversions to occur before within-basin diversions. For multi-ASR networks, water demands belonging to the same category were assigned the same priority regardless of their position in the

Figure 103. Water resource regions (WRR) (numbered) and assessment subregions (ASR) of the conterminous United States.

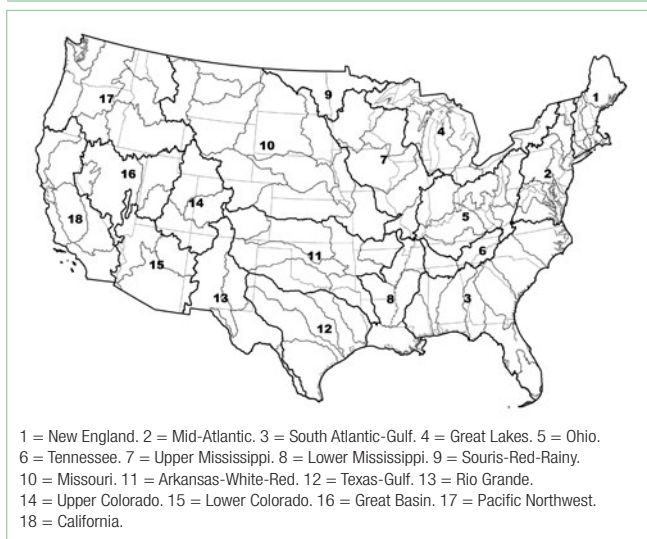
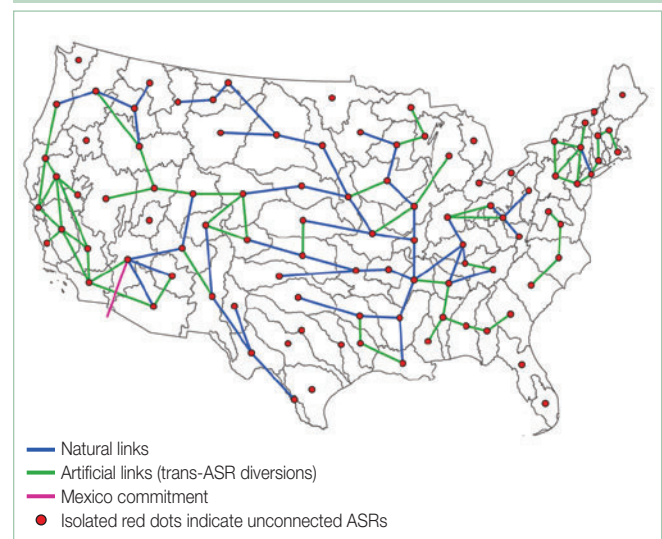


Figure 104. Water networks across the United States at the assessment subregion (ASR) level.



network. Because reservoir storage was assigned the lowest priority level, water is stored in a given year only after all the demands reachable by a reservoir are satisfied. Water stored at the end of 1 year, minus an evaporation loss, is available for use the following year.

Modeling water allocation at the ASR scale makes the aggregate water supply in the ASR available to meet the aggregate water demand in the ASR. It is as if, within an ASR, the water were ideally located to satisfy as much of the total demand as possible, whereas, in fact, it may not be. A more accurate assessment of vulnerabilities could be obtained if the modeling were accomplished at a smaller spatial scale.

To capture in a rough sense the uncertainty about the estimates of vulnerability, water yields and water demands were estimated for each of the RPA scenario-climate combinations discussed previously (table 2), enabling nine separate estimates of vulnerability for each ASR.

Trends in Water Use: Past and Projected

Estimates of water withdrawal across the United States at a fairly fine scale are available at 5-year intervals from the U.S. Geological Survey (USGS) for the period 1985 through 2005 (Hutson et al. 2004; Kenny et al. 2009; Solley et al. 1988, 1993, 1998). Additional USGS water withdrawal data at a larger scale are available for the period 1960 to 1980. These data, along with data on water use drivers and rates of withdrawal per unit of driver, were used to simulate past and current conditions and as a source of information to project future levels of desired water withdrawal (from surface and groundwater combined) by ASR. Consumptive use proportions (the portion of withdrawal that does not return to the stream) from the USGS for years 1985, 1990, and 1995 were then used as the basis for converting estimates of withdrawal to estimates of consumptive use. The resulting estimates of desired consumptive water use, also called demand in this section, were produced for five water use sectors—domestic and public, industrial and commercial, freshwater thermoelectric, agricultural irrigation, and livestock and aquaculture—which were aggregated to a single estimate of demand for modeling vulnerability.

Withdrawal was estimated as number of demand units (e.g., a person for domestic use or an irrigated acre for agricultural use) times the withdrawal rate (withdrawal per demand unit), plus the future withdrawal attributable to climate or other factors that are largely unrelated to past levels of water use. Future levels of withdrawal rates were estimated by extending past trends to show where future water use will go if future supplies are no more constraining to withdrawals than in the recent past.

This extension of past trends, of course, provides an unrealistic estimate of actual future water use for some locations, but suits our objective of showing where adaptation will be needed as population and climatic conditions change. At a large spatial scale, water withdrawal rates in most cases have changed gradually, rather than abruptly, presenting an orderly trend. Extrapolation is an accepted approach for projecting future trends when the past trend has been orderly, and in the absence of detailed knowledge of the underlying mechanisms affecting change or adequate data to model those mechanisms (Wilmoth 1998).

For comparison purposes, future water use was first projected with no future climate effects, using the population and income assumptions of the RPA A1B, A2, and B2 scenarios.¹⁵ Climate effects on water use for the nine RPA scenario-climate combinations were then incorporated. The following six subsections describe past and projected withdrawals and consumptive use for the five water use sectors assuming no future climate change, with the projections corresponding to population and income estimates for the RPA A1B scenario. Those projections are then compared with those of the RPA A2 and B2 scenarios, followed by the introduction of effects of climate change on water use. Results are summarized here for the United States as a whole and sometimes also for eastern and western divisions of the United States, where the eastern division consists of WRRs 1 through 9 and the western division consists of WRRs 10 through 18 (see figure 103).

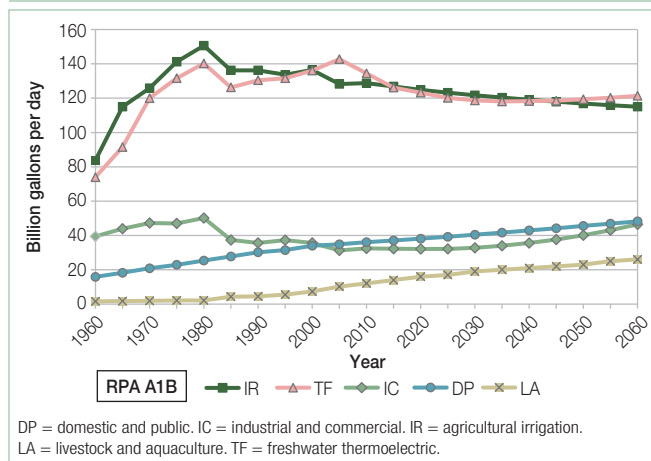
Domestic and Public Withdrawals

From 1960 to 2005, total domestic and public withdrawals in the United States steadily increased, from 16 to 35 billion gallons per day (bgd) (figure 105). The increase in withdrawals reflects the steady growth in population, which rose from 177 to 294 million during that period, and masks an important change in the domestic and public per capita withdrawal rate. Although U.S. per capita domestic and public withdrawals steadily increased from 1960 to 1990, from 90 to 122 gallons per day, since 1990 the nationwide withdrawal rate has leveled off, fluctuating between 118 and 122 gallons per day. The increasing per capita water use from 1960 to 1990 is attributable to a variety of factors, including a decrease in average household size (a certain minimum level of water use per household is largely unrelated to household size), the conversion of older or rural households to complete plumbing, and an increase in use of water-using appliances. 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 during the 1960-to-1990 period (Scheffer 1990).

The leveling off of the per capita domestic and public withdrawal rate may be the result of conservation programs, the

¹⁵ The RPA HFW scenario does not have any assumptions that vary from the RPA A1B scenario for the purpose of the water analysis.

Figure 105. Past and projected annual water withdrawals in the United States by water use type, scenario RPA A1B, no future climate effects, 1960–2060.



expansion of water metering to previously unmetered taps, rising water rates, and the use of more efficient plumbing fixtures in newer homes and renovations, plus the completion of the conversion to modern plumbing and tapering off of the drop in household size (Brown 2000). Although the recent trends in the withdrawal rate do not provide a clear indication of future changes, the most recent change, from 2000 to 2005, was a decrease in the rates of both the eastern and western divisions.

Assuming a small but consistent decrease in per capita domestic and public withdrawals from 118 gallons per day in 2005 to 109 in 2060, and a steady increase in total population, from 294 to 444 million per the RPA A1B scenario, results in a projected gradual increase in total domestic and public withdrawals from 35 to 48 bgd (figure 105).

Industrial and Commercial Withdrawals

Industrial and commercial withdrawals in the United States steadily increased from 1960 to 1980, remained at about 36 bgd from 1985 to 2000, then dropped to 31 bgd in 2005 (figure 105). Because of the great variety of outputs of the industrial and commercial sector, the withdrawal rate is measured per dollar of total annual personal income (in year 2006 dollars). The rate declined from 11 gallons per day per \$1,000 in 1960 to about 3 gallons in 2005. The drop in withdrawal rate 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 service-oriented businesses, and to enhanced efficiency of water use. Efficiency improved in response to environmental pollution legislation, which regulated discharges and thereby encouraged reductions in withdrawals, 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.

The reasons for past declines in the industrial and commercial withdrawal rate—loss of heavy manufacturing plants and ever-present environmental concerns—are likely to continue to play a role, suggesting that recent past trends in the withdrawal rate are a good indication of future changes. Assuming a future drop in the industrial and commercial withdrawal rate from 3.0 gallons per \$1,000 per day in 2005 to 1.3 in 2060, and a steady increase in total annual income from \$11 to \$36 trillion, results in a projected increase in total industrial and commercial withdrawals from 31 bgd in 2005 to 46 bgd in 2060 (figure 105).

Electric Energy Withdrawals

Freshwater use in the electric energy sector depends largely on how much electricity is produced at thermoelectric plants. About 90 percent of the electric energy produced in the United States is generated at thermoelectric power plants (USDOE EIA 2009), which require large amounts of water, mostly to cool and condense the steam used to drive the turbines. From 1960 to 2005, there was relatively little growth in production at hydroelectric and other renewable plants, such that production at thermoelectric plants grew at an impressive rate in response to population growth and the increasing per capita electricity use rate. Largely in response to this increasing production of electricity, freshwater withdrawals at U.S. thermoelectric plants rose rapidly from 1960 to 1980 and somewhat more slowly from 1985 to 2005, reaching 143 bgd (figure 105).

This near-complete reliance on thermoelectric power to accommodate expanding demand is now changing. Although aggregate production at hydroelectric plants is projected to remain roughly at its current level into the future, as the modest additions to capacity serve only to replace losses, production at other renewable plants (e.g., wind and solar), which use very little water, has begun to rise and is expected to continue to rise until at least 2035 (USDOE EIA 2010).

The average water withdrawal rate at freshwater thermoelectric plants dropped consistently from 29 gallons per kilowatt hour (kWh) in 1985 to 20 in 2005, as once-through plants—those that use water only once before returning it to the stream (at a higher temperature)—were retired or converted to recycling plants and as new recycling plants were added to the grid. Although withdrawal rates differ markedly between the East and West—in 2005, the rate was 24 gallons per kWh in the East but only 11 in the West, where recycling is more common—rates in all regions have been consistently dropping. The reasons for past declines in withdrawal rate are likely to continue to play a role, suggesting that recent past trends are a good indication of future changes.

Total annual electric energy production at thermoelectric plants is projected to grow from 2.5 trillion gigawatt hours in 2005 to 3.6 trillion in 2060, as the population increases but renewable

energy sources provide a growing share of total production. Countering this growth in production at freshwater thermoelectric plants is the change in withdrawal rate, which for the United States as a whole is projected to drop from 20 gallons per kWh in 2005 to 12 in 2060. Combining these projections yields a projected total withdrawal at freshwater thermoelectric plants that drops from 143 bgd in 2005 to 118 bgd in 2035, then rises to 121 bgd by 2060 (figure 105).

Irrigation Withdrawals

Total irrigation withdrawals rose rapidly from 1960 to 1980, were stable at about 136 bgd from 1985 to 2000, then dropped to 128 bgd in 2005 (figure 105). This trend reflects most importantly the trend in irrigated acreage, which grew rapidly from 1960 to 1980 and, since 1980, has fluctuated between 58 and 62 million acres. These national totals, however, obscure an important regional difference. Irrigated acres in the arid and semiarid western division, where the vast majority of irrigation occurs, grew steadily from 1960 to 1980, declined steadily from 1980 to 1995, and in 2005 returned to the 1995 level of about 46 million acres. The drop occurred as farmers sold some land or water to cities, industries, and rural domestic users, and as pumping costs, crop prices, and government incentive programs caused marginal lands to be removed from irrigation. Irrigated acreage in the Eastern States grew continuously from 1960 to 2005, to 15 million acres, as farmers moved to rely more on irrigation water to supplement precipitation during dry times (Moore et al. 1990).

Since 1985, the irrigation withdrawal rate in the East has fluctuated between 1.28 and 1.41 feet per acre, and was 1.33 feet per acre in 2005, whereas in the West the rate fell consistently from 2.95 feet per acre in 1985 to 2.70 feet per acre in 2005. The much lower rate in the East is attributable to the higher precipitation levels in the East and to the prevalence of more efficient (sprinkler, drip) irrigation methods. The drop in the West reflects the gradual switch from flood to more efficient irrigation methods.

Irrigated acreage in the West is projected to continue the downward trend begun in the early 1980s, dropping from 46 million acres in 2005 to 42 million acres in 2060. In the East, irrigated acreage is projected to continue to increase, although at a decreasing rate, from 15 million acres in 2005 to 20 million acres in 2060. Total irrigated acreage is projected to peak in 2040 at 63 million acres and drop to 62 million acres in 2060. In the West, the withdrawal rate is projected to continue falling, reaching 2.4 feet in 2060, whereas eastern rates are projected to drop only slightly, reaching 1.3 feet in 2060. Combining these trends yields a drop in annual western irrigation withdrawal from 110 bgd in 2005 to 91 bgd in 2060, and a rise in eastern withdrawals from 18 bgd in 2005 to 23 bgd in 2060, for a total change from 128 bgd in 2005 to 114 bgd in 2060 (figure 105).

Livestock and Aquaculture Withdrawals

U.S. livestock and aquaculture withdrawals increased gradually from 1960 to 1995, then rose more steeply as the aquaculture sector expanded, reaching 10 bgd in 2005 (figure 105). Livestock withdrawal per capita has been dropping since at least 1990, largely because of changing consumer tastes (Haley 2001). In the West, daily per capita withdrawals dropped more than 35 percent between 1990 and 2005, reaching 12.5 gallons in 2005, whereas in the East the rate dropped 10 percent during the same time period, reaching 4.3 gallons in 2005. By 2060, the withdrawal rates are projected to decline to 8.0 gallons per capita per day in the West and 3.9 in the East.

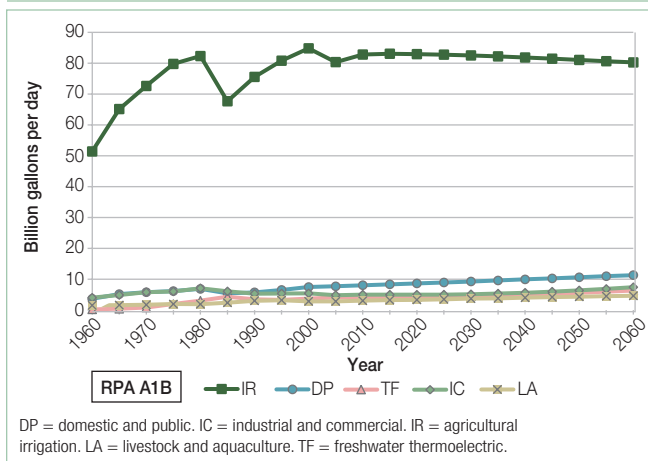
Aquaculture withdrawal per capita per day consistently rose from 1990 to 2005, from 9.9 to 42.7 gallons in the West and from 8.6 to 19.0 gallons in the East. The rate is higher in the West because of the prevalence of coldwater species such as trout, which benefit from a high dissolved oxygen content and are typically farmed using quick once-through withdrawals. Farming of warmwater species, which generally employs more slowly replenished ponds, is more common in the East, especially in the South. The withdrawal rates are projected to reach 72 gallons/capita/day in the West and 39 in the East in 2060. Total livestock and aquaculture withdrawals are projected to increase from 10 bgd in 2005 to 26 bgd in 2060 (figure 105).

Consumptive Water Use

A portion of most water withdrawals returns to the stream and becomes available for additional uses downstream. The quantity that does not return to the stream, called the consumptive use, is the appropriate quantity to compare with available supplies to assess the vulnerability of water supplies to shortages. Consumptive use was computed as a proportion of withdrawals based largely on consumptive use rates estimated from USGS data, as mentioned previously. Minor increases in these proportions are expected in the thermoelectric and irrigation sectors as producers gradually shift to more efficient technologies, and decreases are expected in the livestock and aquaculture sector as aquaculture grows as a percentage of total livestock and aquaculture withdrawal. Consumptive use rates vary widely by water use sector and by region of the country within a sector. The rates tend to be highest in the irrigation and livestock sectors and lowest in the thermoelectric and aquaculture sectors.

Irrigation was estimated to account for 81 percent of total consumptive use in 2005 (figure 106). As irrigation withdrawal lowers and some other withdrawals increase (figure 105), the portion of total consumptive use attributable to irrigation is projected to decrease, to 73 percent in 2060. The domestic and public sector was estimated to account for 8 percent of total consumptive use in 2005, with the other sectors each accounting for less than 5 percent of the total.

Figure 106. Past and projected annual consumptive water use in the United States by water use type, scenario RPA A1B, no future climate effects, 1960–2060.



Other Water Uses

In the effort to decrease our reliance on petroleum, many changes in liquid fuel production are expected in the coming years, most notably a rapid growth of biofuel production. Because processing of liquid fuels from biomass and other nontraditional sources is a relatively new industry, future water use in this sector is not represented in industrial water use projections that are based on past water use, and thus were computed separately.

In production of alternative liquid fuels, water is used for fuel processing and in irrigating some crops used to produce ethanol. Estimates of water use in processing were based on Energy Information Administration projections of future production of corn-based and cellulosic ethanol, biodiesel, and coal-to-liquid fuel needed to meet the renewable fuel standard (RFS) goals of the Energy Independence and Security Act of 2007 (USDOE EIA 2010). Estimates of additional irrigation attributable to ethanol projections were tied to estimates of the effect of ethanol on agricultural acreage (Malcolm et al. 2009). Meeting the RFS goals is estimated to increase total U.S. consumptive water use by 1.3 percent above what would otherwise occur in 2005. This percentage increase diminishes to about 1 percent by 2025 as less water-intensive crops are substituted for corn in ethanol production. Irrigation is projected to account for about 90 percent of the additional consumptive use that is needed in 2010 for production of liquid fuels, a percentage that drops to about 75 by 2060.

Other energy-related water uses involve drilling for oil and gas in shale deposits. The United States has vast oil shale reserves, but U.S. production of oil shale is in its infancy. Extraction of natural gas using newly employed hydraulic fracturing technology is developing as a major new energy source, however. Exploitation of these deposits could use significant quantities of

water, but because of the great uncertainty about future production levels and water needs, we did not attempt to include exploitation of shale deposits as a projected water use.

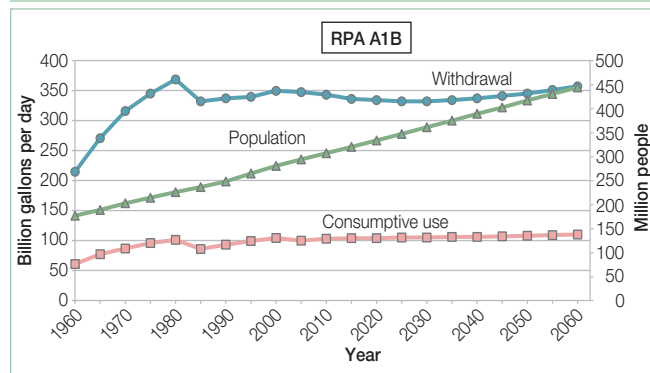
Projected Total Water Use Assuming No Future Climate Effects

Based on past trends, and in the absence of future climate change, water withdrawal rates were projected to decrease in all sectors but livestock and aquaculture. Changes in most drivers of water use—population, per capita income, per capita electricity consumption—are expected to increase pressure on water supplies; the projected decrease in irrigated acreage in the West, however, is an exception to this general trend. Combining these factors, in the absence of future climate change, aggregate U.S. withdrawal is projected to increase by only 3 percent from 2005 to 2060 despite a 51-percent increase in population under the RPA A1B scenario, whereas consumptive use increases by 10 percent (figure 107).

As would be expected given the relative levels of population among the three RPA scenarios, the projected withdrawals and consumptive use of the RPA A1B scenario fall in between the levels of the RPA A2 (higher population) and RPA B2 (lower population) scenarios. With no future climate effects, withdrawals actually decline for many years with the RPA B2 scenario, although they begin to increase slightly after 2050. Withdrawals are slightly greater under RPA A2 than RPA A1B, reflecting greater population growth under RPA A2, but also higher projected income levels under RPA A1B (figure 108).

Projected changes in water withdrawal vary widely among the ASRs. From 2005 to 2060, for the RPA A1B scenario (figure 109), withdrawals are projected to drop in 42 of the 98 ASRs, increase by less than 25 percent in 38 ASRs, and increase by more than 25 percent in the remaining 18 ASRs. The ASRs where withdrawals are projected to drop are rather evenly divided between the East and West, as are the ASRs expecting increases above 25 percent.

Figure 107. Past and projected annual water use and population in the United States, scenario RPA A1B, no future climate effects, 1960–2060.



Projected Water Use Under a Changing Climate

We now add in the future climate change effects to compute projected future water use for the nine RPA scenario-climate combinations. The effects of climate change on water withdrawals were estimated for irrigation use based on changes in precipitation and potential evapotranspiration, for domestic and public use based on changes in precipitation and potential evapotranspiration, and for thermoelectric use based on temperature changes. Whereas temperature is projected to increase everywhere (although more in some areas than others), precipitation is projected to increase in some areas and decrease in others. The precipitation projections of the different general circulation models (GCMs) differ considerably, yielding a range of resulting changes in water withdrawal. The primary climate change effect is that of potential evapotranspiration changes on plant water demand, most importantly in irrigated agriculture and secondarily in domestic and public landscape

Figure 108. Past and projected water withdrawals in the conterminous United States, by RPA scenario, no future climate effects, 1985–2060.

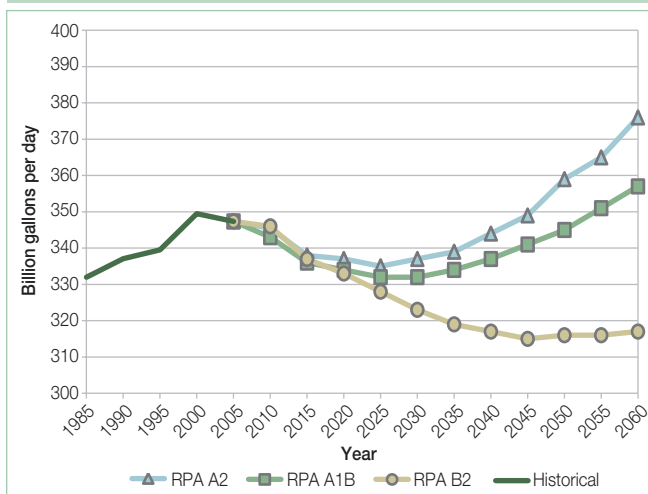
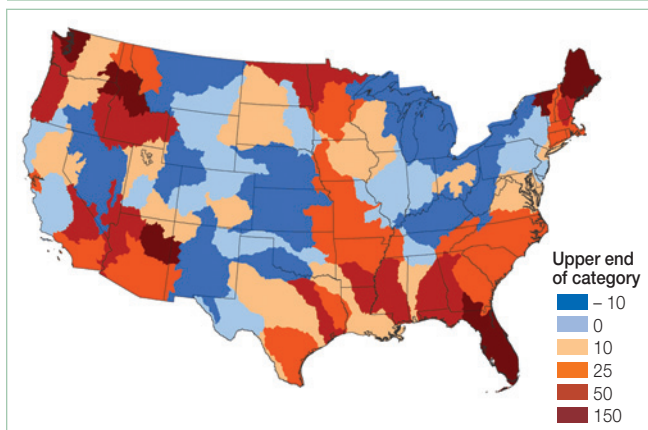


Figure 109. Percent change in projected water withdrawal, by assessment subregion (ASR), RPA A1B scenario, no future climate effects, 2005–2060.



maintenance. In the thermoelectric sector, the primary effect is expected to be temperature increases on space cooling, which almost always relies on electricity.

Climate change is projected to increase water use substantially. For example, under the RPA A1B scenario, and averaging results from the three associated GCMs, U.S. withdrawals are projected to increase from 2005 to 2060 by 26 percent as compared with only 3 percent without future climate change. Of the 23-percent difference, 76 percent is due to increases in agricultural irrigation, 10 percent to increases in landscape irrigation, and 14 percent to increases in withdrawals at thermoelectric plants to handle the increase in space cooling demand. There is great variation across the RPA scenario-climate combinations in both projected withdrawals (figure 110) and consumptive use. Projections for 2060 vary from 354 bgd with the RPA B2-CSIRO-Mk3.5 future to 493 bgd with the RPA A2-MIROC3.2 future. Given the 2005 withdrawal level of 347 bgd, these projections for 2060 represent increases of 2 and 42 percent, respectively. The MIROC3.2 model projects the highest temperatures and lowest precipitation levels of the four GCMs for 2060.

Similar to the results under the assumption of no future climate change (figure 109), there is wide spatial variation in projections of future water withdrawals under a changing climate (figure 111). From 2005 to 2060, based on a GCM multimodel average, withdrawals under the RPA A1B scenario are projected to drop in 11 ASRs and increase by less than 25 percent in

Figure 110. Past and projected water withdrawal for the conterminous United States for nine RPA scenario-climate combinations and RPA A1B with no future climate effects, 1985–2060. Future years are multiyear averages.

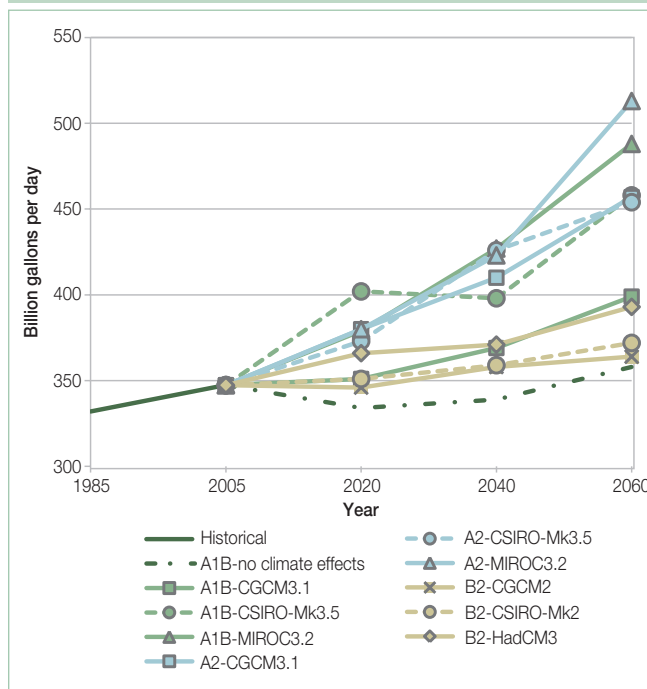
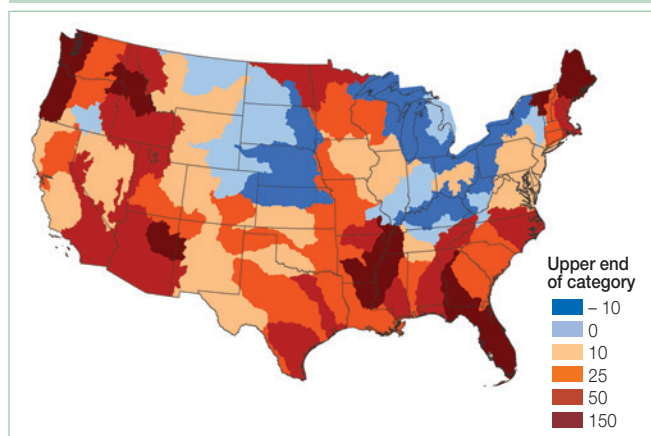


Figure 111. Percent change in projected water withdrawal, by assessment subregion (ASR), RPA A1B scenario, with climate effects (multimodel average), 2005–2060.



37 ASRs, by from 25 to 50 percent in 35 ASRs, and by more than 50 percent in the remaining 15 ASRs. The ASRs where withdrawals are projected to drop are mostly in the East, but ASRs where withdrawals are projected to increase by more than 50 percent are scattered across the country.

Projected increases in consumptive use remain much less than 50 percent throughout much of the West regardless of RPA scenario or climate projection, whereas projected increases in the East often reach well above 50 percent, especially for scenario RPA A2. This regional difference reflects principally the projected changes in irrigated acres in these two broad regions of the United States, with decreases in the West and increases in the East.

These projections, and the GCM models on which the projected effects of climate change rely, are educated guesses. The wide ranges highlight the uncertainty about the effects of increases in greenhouse gases on temperature and precipitation across the United States. Although we cannot be sure that the ranges reported here span the full extent of the future possibilities, it is notable that with all nine RPA scenario-climate combinations the long-term effects of climate change are always to increase aggregate water demands. Further, the principal effect is that of increasing temperature on vegetative water demand (for agricultural irrigation and landscape maintenance), not that of increasing temperature on electricity demand or of changing precipitation. Increasing precipitation in some locations ameliorates the effect of temperature increases, but precipitation increases, where they occur, are insufficient to balance out the temperature effect.

Aside from the projections of climate variables, perhaps the most crucial assumption made for projecting future water demand is that about future irrigated area, because irrigation accounts for the bulk of consumptive use and because irrigation requirements are more sensitive than the other water use categories

to climate changes. Although recent trends in irrigated area provide some basis for extrapolation, unexpected changes in world markets for agricultural products could easily alter the trajectory.

Future Water Supply

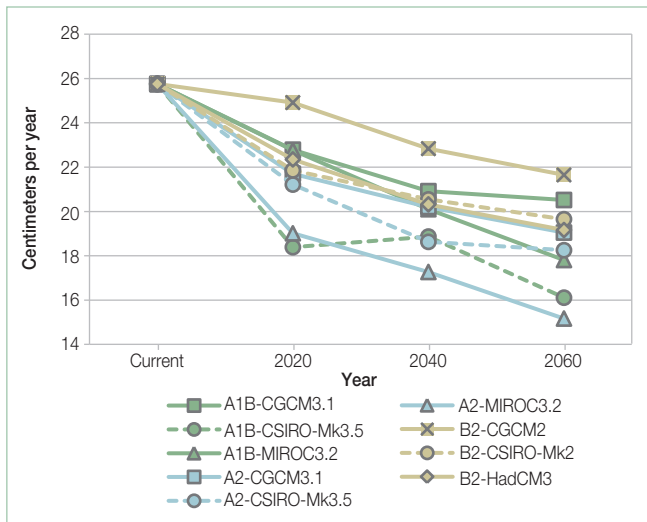
The water supply of an ASR is its water yield as modified (either amplified or diminished) by water redistribution (via natural flow and artificial diversions) and storage, as explained previously. Water yield, the sum of surface and subsurface runoff, was estimated as precipitation minus evapotranspiration using Eagleson's (1978) annual water balance model. The water yield model was implemented on a 5x5-kilometer grid for the United States and calibrated using three different streamflow datasets of measured or reconstructed natural flows.

In light of the lack of comprehensive information on the direct effects of elevated atmospheric carbon dioxide on plant water use across the various ecological conditions (e.g., mature forest, young forest of various species, agricultural crops) (Tubiello et al. 2007), these estimates assume no regional-scale direct effect of increasing carbon dioxide on plant water use per unit area. The major cause of the decrease in future water yield is the general increase in potential evapotranspiration that all GCMs project. Further, the water yield estimates do not reflect the effect of changing vegetation as the climate and land uses change over time.

Using annual temperature, precipitation, and potential evapotranspiration estimates from downscaled global climate model output, the water yield model was used to estimate future yield, and yield estimates were then aggregated to the ASR scale. For the United States as a whole, water yield is projected to decrease throughout the 21st century (figure 112). Considerable uncertainty surrounds the overall level of decrease, however. Projections differ by RPA scenario and by climate projection for a given scenario. Using the results from the CGCM3.1 and CGCM2 GCM models, for example, average annual yield decreases of 16, 22, and 17 percent are projected by 2060 under the RPA A1B, A2, and B2 scenarios, respectively. Taking the RPA A1B scenario as an example, average annual yield decreases of 22, 16, and 18 percent are projected by 2060 with the CGCM3.1, CSIRO-Mk3.5, and MIROC3.2 models. The variation in projected yield is primarily the result of differences among the models in estimates of temperature and precipitation.

Decreases in yield are projected for most but not all ASRs, as indicated in figure 113, which shows changes in yields for three RPA scenario-climate combinations. In general, the magnitude of the decrease is larger in humid areas (the Eastern United States and along the northwestern coast). Increases are projected for a few arid basins, most often in the Southwest (figure 113). The unexpected increases in average annual yield occur,

Figure 112. Mean annual water yield in the conterminous United States, by RPA scenario-climate combination for four 20-year periods. “Current” yield is evaluated over the 20-year period, 1986–2005. Future yield is estimated for three 20-year periods centered at 2020, 2040, and 2060.



despite increasing potential evapotranspiration and sometimes decreasing precipitation, because of increases in the *variance* of projected precipitation and potential evapotranspiration; an increasing variance produces higher flows in wet times, whereas flows during dry times can only drop to zero. Increases in average yield are more likely in arid climates because of their highly skewed distributions of precipitation and water yield. Note that the increases in average yield are very small in absolute terms.

As mentioned, supply depends not only on water yield but also on storage capacity, transbasin diversions, and instream flow requirements. Reservoir storage capacity for each ASR was determined by aggregating the normal storage capacities of natural and humanmade impoundments for the 1,196 reservoirs with a normal surface area of at least 5 square kilometers based on the U.S. Army Corps of Engineers National Inventory of Dams (USACE 2009). Storage capacities of the ASRs range to more than 40 million acre-feet for an ASR along the Missouri River (figure 114). Thirteen ASRs have at least 10 million acre-feet of storage. Reservoir evaporation was estimated from storage-to-surface area relationships and estimates of potential evaporation.

Information on trans-ASR diversions—water diverted from one ASR to another, usually as a result of legal agreements between jurisdictions—is scattered and difficult to gather. We relied on summaries by the USGS (Mooty and Jeffcoat 1986; Petsch 1985), supplemented by more recent information when available (California Department of Water Resources 1998; Colorado Water Conservation Board 1998, 2010; Litke and Appel 1989).

Figure 113. Change from current conditions to 2060 in assessment subregion (ASR) mean water yield (centimeters per year), based on comparing 20-year periods centered at 1996 and 2060, for a sample of RPA scenario-climate combinations: (a) RPA A1B-CGCM3.1; (b) RPA A2-CSIRO-Mk3.5; and (c) RPA B2-HadCM3.

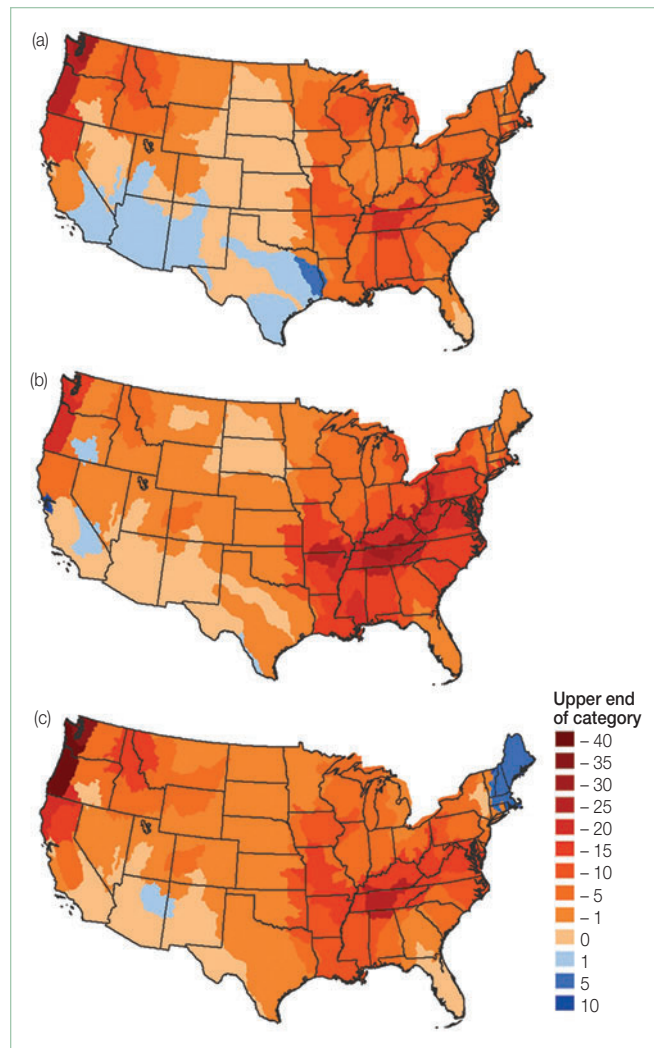
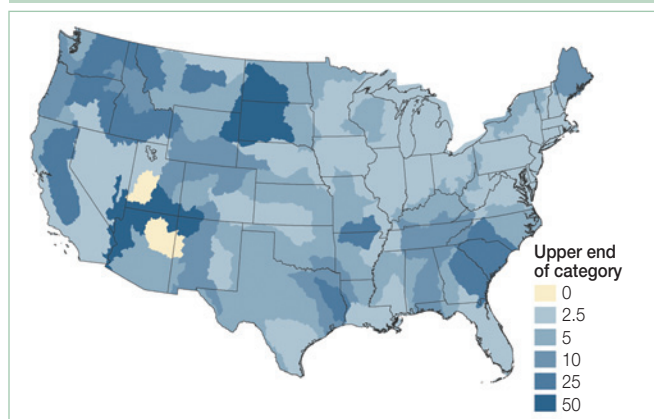


Figure 114. Assessment subregion (ASR) water storage capacity (million acre-feet).



Instream flow requirements are meant to ensure adequate supply for downstream users, including ecosystems, recreation, and hydropower. Determination of instream flow requirements involves a complicated mix of socioeconomic, biological, and environmental factors, which is not practical at the ASR scale. Because instream flow requirements cannot be ignored, we adopt the general guideline of Tennant (1976) and set the instream flow requirement of each ASR for both current and future conditions at 10 percent of average historical streamflow, computed from data for the period 1953 through 1985.

Vulnerability of U.S. Water Supply

Vulnerability, the probability that supply is less than demand, was computed for each of the 98 ASRs in the United States for current conditions and for future conditions of each of the 9 RPA scenario-climate combinations. Each estimate of vulnerability was based on 20 years of simulation, which were used to estimate distributions of vulnerability and other key variables (Foti et al., in press). Supply of an ASR in a given year was computed as water yield within the ASR plus inflow from upstream and net transbasin diversion into the ASR minus releases to downstream ASRs, with movements of water into and out of an ASR determined by the network model given the priorities imposed and storage capacities available.

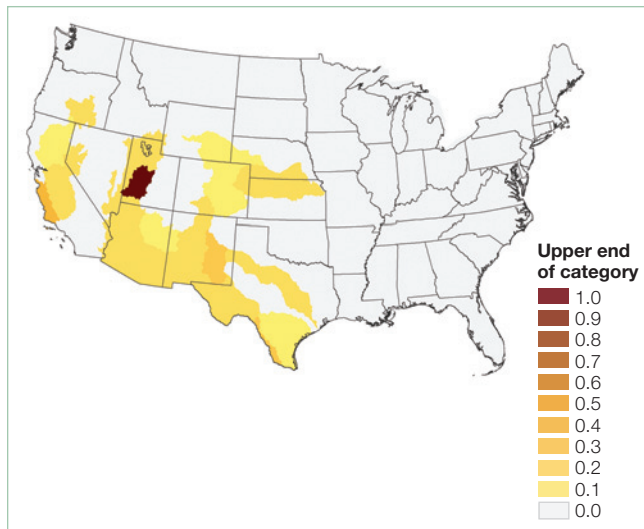
Current Vulnerability

The climate of the period 1986 through 2005 was taken as the *current* climate. The water supply systems of four-fifths of the western ASRs and about one-third of the eastern ASRs are vulnerable under current hydroclimatic and socioeconomic conditions, although in most ASRs the probability of shortage is less than 0.1 (figure 115). The most vulnerable ASRs tend to rely heavily on groundwater mining, a nonrenewable source of water that was not included in water supply as estimated for this analysis. This constraint should not detract from the principal focus of the RPA Assessment, which is the change in vulnerability from the current situation to the future. Some localized, within-ASR areas that are known to have faced shortages in the past are not revealed as areas of shortage at the ASR scale. This situation is most likely for areas located in the upper reaches of an ASR, which places them upstream of the bulk of the available water supply in the ASR, as in the case of Atlanta (Feldman 2009).

Future Vulnerability

Traces of future water yield for the period 2006 through 2060 and beyond were obtained by applying the water balance model using the climatic estimates of the nine RPA scenario-climate combinations. Each simulation used a distinct sequence of

Figure 115. Current probability of annual water shortage.



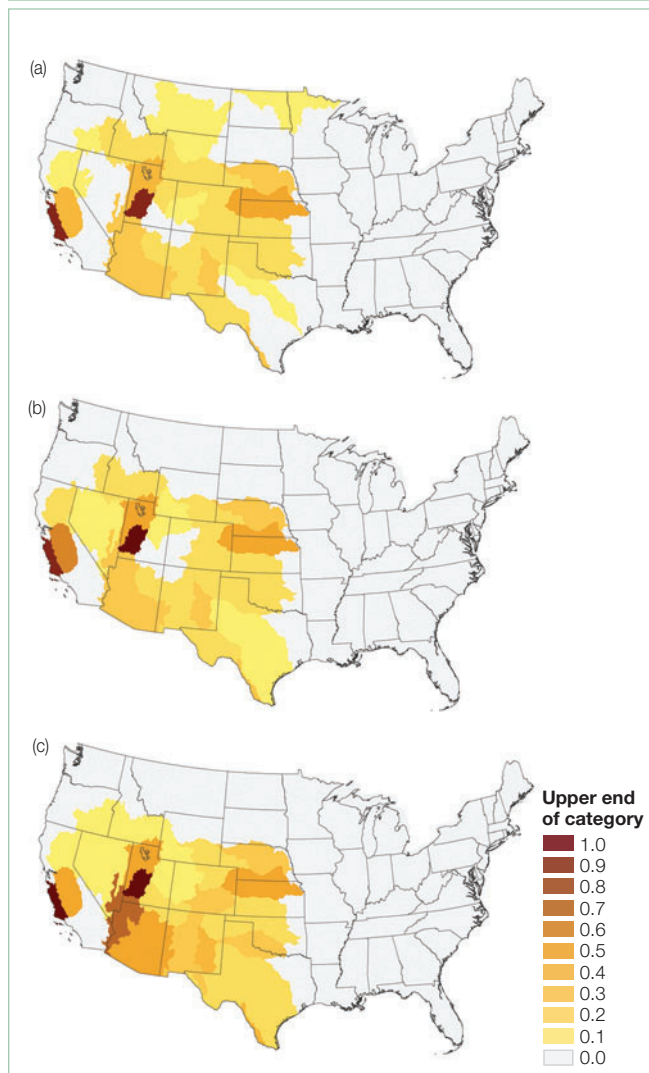
water demands that also reflect the climatic projections. The physical structure of the water network (links and nodes configuration), operating rules, storage capacities, and transbasin diversions were left unchanged for all simulations.

Vulnerability was assessed for years 2020, 2040, and 2060, each estimate representing 20-year periods centered at those years. Increases in vulnerability are projected to occur mainly in arid and semiarid areas of the United States where the current conditions are already precarious (figures 116 to 119). Most of the Eastern United States, on the other hand, is currently characterized by water abundance, and no eastern ASRs exhibit a probability of shortage greater than 0.1.

Vulnerability tends to increase over time as the effects of climate change become larger (figure 116). For a given RPA scenario, projected levels of vulnerability differ considerably across the climate models used (figures 117, 118, and 119). Compared with the RPA A1B scenario (figure 117), vulnerability is generally greater with the RPA A2 scenario (figure 118) and generally less with the RPA B2 scenario (figure 119). These differences are expected, given the higher population and temperatures in the RPA A2 scenario and lower levels of those variables in the RPA B2 scenario, especially later in the century. Notably, in all cases, the increases in vulnerability largely occur in the southwestern part of the country (California, the Southwest, the Great Basin, and the central and southern Great Plains).

The increasing vulnerability, evident by comparing figure 115 with figures 116 through 119, results mainly from the decreasing water supply and increasing water demand caused by the changing climate. Increase in population and economic activity alone are comparatively minor sources of the increasing vulnerability. Although decreasing precipitation (where it occurs) and

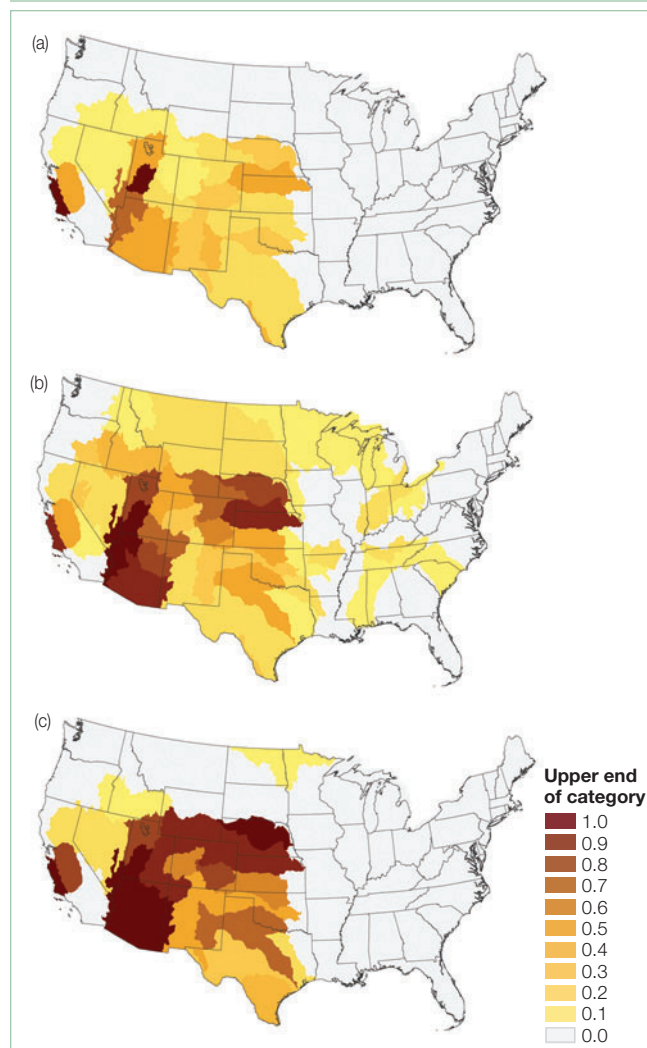
Figure 116. Vulnerability (probability of shortage) for RPA A1B-CGCM3.1, in the year (a) 2020, (b) 2040, and (c) 2060.



increasing potential evapotranspiration both lead to decreases in water supply, the major effect comes from increases in evapotranspiration.

Furthermore, we find that in roughly half of the ASRs, future increases in the vulnerability of the water supply to shortage will depend more on decreases in water yield than on growth in water demand; in the remaining ASRs, the reverse is true. Total water use in the United States has leveled off in recent years, as irrigated area in the West has diminished and the efficiency of water withdrawals in nearly all sectors has improved. Although climate change will increase water demand, future water use efficiency improvements will mitigate that effect so that overall increases in desired water use in many ASRs are expected to be modest in comparison with the climate-induced decreases in water yield and thus in water supply.

Figure 117. Vulnerability (probability of shortage) for the RPA A1B scenario in 2060 using the following climate models: (a) CGCM3.1, (b) CSIRO-Mk3.5, and (c) MIROC3.2.



These results assume no modifications to the physical structure of U.S. water networks. In addition, instream flow requirements and trans-ASR diversions were set constant, thereby ignoring possible future changes in surface water redistribution. Indeed, it is the purpose of this analysis to point to those locations where adaptation (e.g., larger transbasin diversion capacity or within-basin water transfers and enhanced water conservation) will be most needed. The simulations project a persistent decline in reservoir storage for many of the ASRs of the larger Southwest, with storage reaching zero and never returning to capacity in 10 of those ASRs, most notably in the ASRs along the Colorado River that contain Lakes Powell and Mead. This projected decline indicates that water scarcity there occurs primarily because of supply-demand imbalance rather than insufficient storage capacity, suggesting that increasing storage capacity there is probably not a successful adaptation strategy.

Figure 118. Vulnerability (probability of shortage) for the RPA A2 scenario in 2060 using the following climate models: (a) CGCM3.1, (b) CSIRO-Mk3.5, and (c) MIROC3.2.

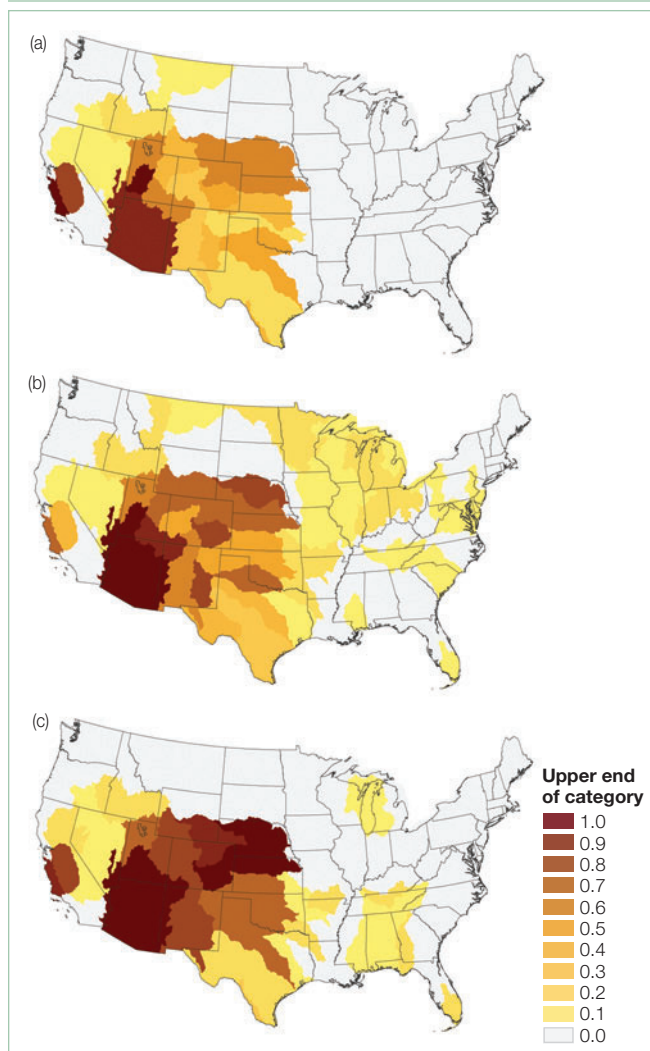
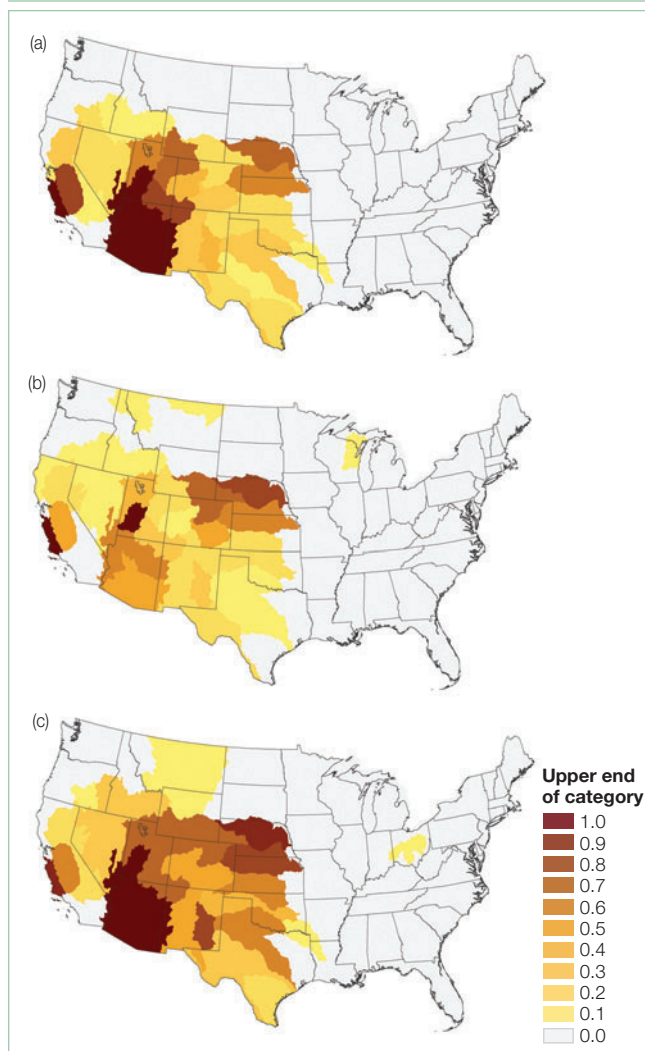


Figure 119. Vulnerability (probability of shortage) for the RPA B2 scenario in 2060 using the following climate models: (a) CGCM2, (b) CSIRO-Mk2, (c) HadCM3.



The simulations do show that some other ASRs of the larger Southwest might benefit from additional storage capacity, however. In addition, note that these results apply to aggregate ASR storage, and thus do not preclude the possibility of useful additions to storage in selected upstream locations.

As figures 117 to 119 make clear, there is much uncertainty about the precise levels of vulnerability projected for the ASRs of the United States. The utility of this assessment is not in its exact estimates of vulnerability but rather in the general pattern of changes in vulnerability that emerges—indicating that ASRs of the larger Southwest are likely to face substantial adaptation challenges—and in the finding that, except in a few ASRs or in selected, generally upland, locations, major additions to reservoir storage capacity would probably not be helpful.

Conclusions

Estimates of future conditions are inherently uncertain. This uncertainty is highlighted by the variation in projected vulnerability among the nine RPA scenario-climate combinations. Additional uncertainty arises because the water yield, water use, and downscaling models used with all of those combinations rely on numerous assumptions and judgment calls. That said, this RPA Assessment represents a concerted effort to realistically project future water demand and supply.

Assuming a stable climate, aggregate water withdrawal in the United States is projected to rise by 2060 by only 3 percent under the RPA A1B scenario. This low level of increase is projected to occur because expected future improvements in the

efficiency of water use largely balance out the effects of population and income growth. Correspondingly, consumptive use is projected to increase by 10 percent. Climate change has the potential to greatly increase water demands, however, especially in the agricultural and domestic sectors because plant water demands increase as the ambient temperature rises, all else equal. Again assuming the RPA A1B scenario, aggregate water withdrawal is projected to increase by from 12 to 41 percent depending on which climate model is used. Corresponding increases in aggregate consumptive use with the RPA A1B scenario range from 26 to 86 percent. Projections are higher for the RPA A2 scenario and lower for the RPA B2 scenario. With all RPA scenarios and climate projections, decreases in water demand are projected for some ASRs, especially in the eastern portion of the country, but most ASRs would face increased demands.

Aggregate water yield is projected to decrease with all RPA scenario-climate combinations. For example, with the RPA A1B scenario water yield is projected by 2060 to decrease by from 16 to 22 percent depending on which GCM is used. Greater decreases are projected for the RPA A2 scenario. Decreases are projected for nearly all ASRs, and any increases are very small in absolute terms.

When assessed at the ASR scale, the larger Southwest—including parts of California, the southern Rocky Mountain States, and the central and southern Great Plains—is projected to face significant water shortages. Most scenario-climate combinations show the probability of shortage in any one year reaching above the 0.5 level in several basins. The highest vulnerability levels occur with the RPA A2 scenario. The CSIRO model yields the most widespread positive vulnerability, but the MIROC model tends to yield the most ASRs with vulnerability levels above 0.5.

These projections of vulnerability are of course not a prediction of future conditions. Clearly they are based on unsustainable levels of water use. Rather, the projections show the portions of the country that, based on current evidence, are likely to face the challenge of bringing water demand more in balance with water supply. Achieving such a balance would certainly include lowering water demand but may also include some efforts to increase supply. Note also that the projections are for renewable water resources (they do not allow for water mining) and assume that a minimum level of instream flow is maintained. The projected levels of vulnerability suggest that drier areas of the United States will continue to experience pressures to mine groundwater and deplete streamflow.