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Projected freshwater withdrawals in the United States under a changing climate

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[1] Relying on the U.S. Geological Survey water use data for the period 1960–2005, this paper summarizes past water use and then projects future water use based on the trends in water use efficiency and major drivers of water use. Water use efficiency has improved in most sectors. Over the past 45 years, withdrawals in industry and at thermoelectric plants have steadily dropped per unit of output. In addition, domestic and public withdrawals per capita, and irrigation withdrawals per unit area in most regions of the west, have recently begun to decrease. If these efficiency trends continue and trends in water use drivers proceed as expected, in the absence of additional climate change the desired withdrawals in the United States over the next 50 years are projected to stay within 3% of the 2005 level despite an expected 51% increase in population. However, including the effects of future climate change substantially increases this projection. The climate-based increase in the projected water use is attributable mainly to increases in agricultural and landscape irrigation in response to rising potential evapotranspiration, and to a much lesser extent to water use in electricity production in response to increased space cooling needs as temperatures rise. The increases in projected withdrawal vary greatly across the 98 basins examined, with some showing decreases and others showing very large increases, and are sensitive to the emission scenario and global climate model employed. The increases were also found to be larger if potential evapotranspiration is estimated using a temperature-based method as opposed to a physically based method accounting for energy, humidity, and wind speed.

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1. Introduction

[2] Offstream water use in the United States increased over 10-fold during the twentieth century in response to tremendous population and economic growth. Although water use efficiency is now improving in many sectors, further rapid growth in population is almost certain to occur, placing additional demands on water supplies. As withdrawals have increased, more water has been consumed, leaving less in the stream. Adding to these stresses, climate change, including rising temperatures and in some locations declining precipitation as well, is likely to decrease water yield. These conflicting trends raise concerns about future water shortages.

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[3] The adequacy of a water supply depends on how water availability compares with demands for its use. This paper focuses on the latter of these two concerns. It estimates future water use in the United States assuming that water supply will be no less limiting to future demands than it has been to past growth in demand. The projections provide a basis for comparison with an expected future supply. Such a comparison shows where shortages would occur in the absence of either new sources of supply or alterations in the projected demand, providing a basis for policy makers and stakeholders to consider possible adaptations.

[4] Ideally, we could accurately forecast future water use. However, producing accurate forecasts would require a comprehensive model of water demand and supply that is applicable in all water basins of interest as well as accurate forecasts of the levels of the independent variables of that model. Acknowledging the implausibility of accurately modeling all of the factors affecting water use over large spatial scales, the overall approach taken here is to develop projections, as opposed to forecasts, and to limit complexity so that the underlying assumptions are relatively few and their impact on the results is transparent. Projections aim not to predict the future but rather to show what will happen if past trends and other established tendencies are extended into the future. This, after all, is the most realistic

Table 1. Projections of U.S. Water Withdrawals for Three Future Years Based on Medium or Best Guess Assumptions, Compared with Actual Withdrawals in 2000, in km^3/yr

	2000	2020	2040
Senate Select Committee on National Water Resources [1961]	1267		
U.S. Water Resources Council [1968]	1111	1890	
Wollman and Bonem [1971]	741	1239	
National Water Commission [1973]	1382	1969[a]	
U.S. Water Resources Council [1978]	423		
Guldin [1989]	532	637	728
Brown [2000]	473	484	503
Actual [*Hutson et al.*, 2004]	477		

[a]Midpoint of the reported range.

objective of future-oriented water resource assessments [*Oki and Kanae*, 2006].

[5] Large-scale projections of water use in the United States have been attempted several times (Table 1). The projections from the 1960s and the early 1970s failed to notice the improving efficiency in industrial and thermoelectric water use that we now know was occurring as far back as 1960, and thus grossly overestimated future water withdrawals. By the time of the Water Resource Council's 1978 projection, data on the early efficiency gains were available. However, in comparison with what ensued, the Council was overly optimistic about further improvements in water use efficiency in the manufacturing, thermoelectric, and irrigation sectors. Because the Council anticipated that the early rate of efficiency improvement would be maintained, and because it underestimated future population growth, its projection for 2000 was below what came to pass. In 1989, Guldin went in the other direction, assuming no further gains in water use efficiency beyond those already achieved by 1985. Thus, despite underestimating the future population, he overestimated the year 2000 withdrawals. Of course, these past projections cannot be faulted for failing to accurately estimate future use. Nevertheless, projections that do not reflect past trends and how those trends are gradually changing are less than ideal tools for assessing future possibilities.

[6] By the late 1990s when *Brown* [2000] projected future water use, there was a 35 year record of changes in the efficiency of water use, based largely on the U.S. Geological Survey (USGS) effort to periodically estimate water use, providing a rich historical base for projections. Brown's projections for 2020 and 2040 (Table 1) are considerably below earlier projections (though not necessarily below what the Water Resources Council in 1978 would have projected if their projections had extended that far into the future). In light of expected further gains in water use efficiency, especially in the industrial, thermoelectric, and agricultural sectors, Brown's projections indicated a 10% increase in nationwide withdrawals by 2040 despite a 41% increase in population.

[7] We now have a 45 year historical record from which to gauge nationwide trends in water use efficiency and thus a better than ever opportunity to produce projections that reflect past trends. Using that record, this study projects future water withdrawals in the United States to 2090. It is recognized that the viability of a projection is inversely related to its time span, i.e., projections far into the future have a tenuous connection to future reality. The projections are nevertheless carried out to 2090 in order to demonstrate the possible impact of climate change, which becomes much more significant during the latter part of the century.

[8] The increasing globalization of the world economy and the likelihood of substantial climatic change have created considerable uncertainty about future water demand (and supply) in the United States. To capture this uncertainty, we adapted three global socioeconomic scenarios developed for the Intergovernmental Panel on Climate Change (IPCC). Each scenario was modeled using three different global circulation models (often called GCMs or simply global climate models), resulting in nine different future climates for which future water use was projected.

2. Methods in General

[9] The approach taken to project future water withdrawals relies, by and large, on projections of the drivers of water use (e.g., population) and extrapolation of the past trends in water use efficiency (e.g., domestic water use per capita). Because of data limitations, the projections are limited to the contiguous 48 states, hereafter referred to as the "U.S." Projections were prepared for 98 assessment subregions (ASRs) covering the U.S. (Figure 1). ASRs, which were originally delineated by the *U.S. Water Resources Council* [1978] and changed only slightly for this analysis, allow analysis of large regional differences within 18 water resource regions (WRRs, Figure 1) yet are large enough to support the use of county-level data.

[10] From the IPCC Fourth Assessment set of global socioeconomic scenarios, the following three scenarios were chosen to characterize future population and income levels: the A1B, A2, and B2 scenarios modeled using the AIM, ASF, and Message global emissions models, respectively [*Nakicenovic et al.*, 2000]. The A1B scenario expects a high level of technological change and rapid spread of new and efficient technologies, with a balanced emphasis on all energy sources. This scenario most closely extends historic population and economic growth patterns. In comparison with the A1B scenario, the A2 scenario expects a lower rate of technological change and higher population growth, and the B2 scenario expects slower population growth but also a lower rate of technological change, with more emphasis on environmental protection. Of the three scenarios, the A2 scenario results in the highest and B2 the lowest atmospheric CO_2 concentration.

[11] Water withdrawal (W) (surface and ground water combined) for a given water use sector and future year was estimated as:

$$W = U \cdot \Phi + \Delta W, \tag{1}$$

where U is the number of demand units such as a person for domestic use or an irrigated acre for agricultural use, also called a water use driver; Φ is the withdrawal per demand unit, also called a water use efficiency factor; and ΔW is the future withdrawal attributable to future climatic changes. Estimates of the projected levels of U and Φ are obtained by extending past trends, whereas estimates of

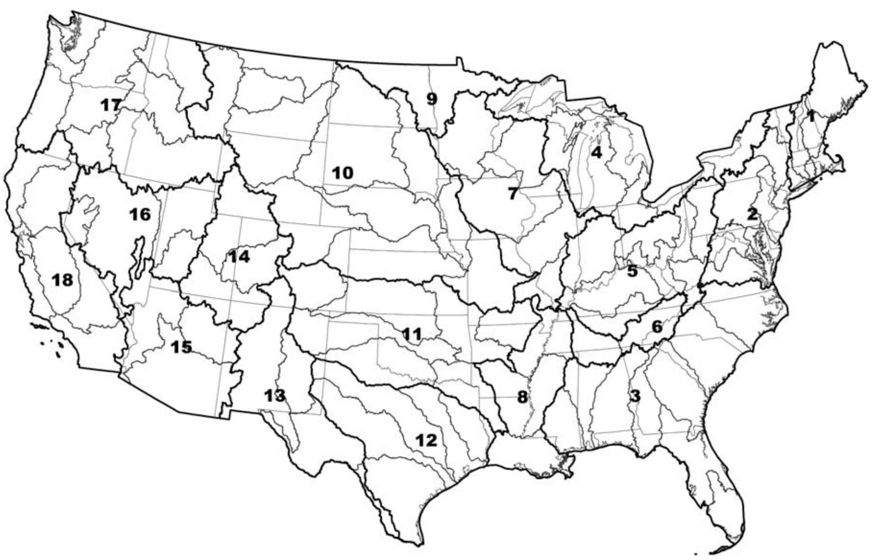

Figure 1. WRRs (numbered) and ASRs.

ΔW represent new influences that will alter the trajectory of U or Φ.

[12] Past trends in the water withdrawal efficiency (Φ) in most cases have been nonlinear, with the rate of change gradually diminishing [*Brown*, 2000]. Extrapolation of past trends in Φ was accomplished by applying an annual growth rate (g) based on the data from recent years and a corresponding decay in that growth rate (d). The decay rate was chosen to attenuate the trend, leading gradually toward a hypothesized equilibrium level (which is not necessarily reached by 2090). Estimates of Φ were developed at the WRR level, as past trends at the ASR level appeared erratic, perhaps due to the weather fluctuations or errors in estimating water use. Given a 5 year time step for projecting withdrawals, the extrapolation procedure for a given year (Y) and WRR is as follows:

$$\Phi_{\mathrm{WRR},Y} = \Phi_{\mathrm{WRR},Y-5}\left(1 + g_{\mathrm{DIV}}\left(1 + d_{\mathrm{DIV}}\right)^{Y-\mathrm{LDY}}\right)^{5}, \qquad (2)$$

where LDY is the last year for which withdrawal data were available (typically 2005), and DIV is a major division of the U.S. Thus, the year 2015 estimate is based on the year 2010 estimate, the year 2020 estimate is based on the 2015 estimate, etc., with the exception that the first projected year, 2010, is typically based on the two most recent estimates, those for 2000 and 2005. Equation (2) is the standard formula for computing the compound effect of periodic growth on the aggregate level of some variable, but with the growth rate (g) itself subject to the effect of an another periodic growth rate (d). If d is negative, g gradually declines. Variables g and d of equation (2) were estimated for eastern (specified as WRRs 1–9) and western (WRRs 10–18) divisions of the U.S. because trends at the WRR scale were often erratic. The annual growth factor (g) was computed from all or part of the record from 1985 to 2005.

[13] Freshwater withdrawals were projected based most importantly on withdrawal data from the USGS's quinquennial compilations over the period 1960−2005, presented in the following circulars: *MacKichan and Kammerer* [1961], *Murray* [1968], *Murray and Reeves* [1972, 1977], *Solley et al*. [1983, 1988, 1993, 1998], *Hutson et al*. [2004], and *Kenny et al*. [2009]. In keeping with the reports on years up to 1995, water use was projected for the following water use sectors: (1) domestic and public (DP), (2) industrial, commercial, and mining (IC), (3) freshwater thermoelectric power (TF), (4) irrigation (IR), (5) livestock (LS), and (6) aquaculture (AQ) (when the LS and AQ sectors are combined for presentation, the joint sector is labeled LA). Because the two most recent water use circulars did not apportion public supplies by water use category, we relied on allocation proportions computed from the 1995 circular. 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. "Irrigation" consists mainly of crop irrigation but also includes self-supplied irrigation of parks, golf courses, turf farms, and other large irrigated landscape areas when they are not included in the domestic and public or industrial and commercial sectors.

[14] Table 2 lists the six water use sectors and the nonclimatic factors used to project water withdrawal for those sectors. Some of these factors are withdrawal efficiency measures (Φ), and others are drivers of consumption (U). Total population was used directly as a factor in estimating future withdrawals for five of the water use sectors (Table 2). In addition, personal income was used to estimate future industrial and commercial withdrawals, irrigated area was used to estimate future irrigation withdrawals, and electricity use was used to estimate thermoelectric water withdrawals. Still other factors were used to bridge the gap from U to Φ. For industrial and commercial water use, income per person was used to link population to withdrawal per dollar of income, and for thermoelectric use, electricity consumption per person was used to link population to electricity use (with additional computations to account for the amount of the total electricity supply that is provided at hydroelectric and other nonthermal plants).

[15] To summarize, water withdrawal in an ASR in a given year Y was estimated as

Table 2. Nonclimatic Factors Used to Project Annual Freshwater Withdrawal From 2010 to 2090

Water Use Sector	Factor
DP	Population
	Withdrawal/person
IC	Population
	Dollars of income/person
	Withdrawal/dollar of income
TF	Population
	Total electricity use/person
	Fresh thermoelectric production/total electricity production
	Withdrawal/fresh thermoelectric kWh produced
IR	Area irrigated
	Withdrawal/unit area
LS[a]	Population
	Withdrawal/person
AQ	Population
	Withdrawal/person

[a]The combination of LS and AQ is referred to as the LA sector.

$$W_{\mathrm{ASR},Y} = W^{\mathrm{DP}}_{\mathrm{ASR},Y} + W^{\mathrm{IC}}_{\mathrm{ASR},Y} + W^{\mathrm{TF}}_{\mathrm{ASR},Y} + W^{\mathrm{IR}}_{\mathrm{ASR},Y} + W^{\mathrm{LS}}_{\mathrm{ASR},Y} + W^{\mathrm{AQ}}_{\mathrm{ASR},Y}. \tag{3}$$

[16] Each component of equation (3) was estimated using equation (1). In most cases the drivers were estimated at the ASR level, and the efficiency factors were estimated, using equation (2), at the WRR level and applied to all ASRs within the WRR. For thermoelectric and irrigation withdrawals, however, both the drivers and efficiency factors were estimated at the WRR level, and the withdrawal estimates for WRRs were then apportioned to ASRs based on the data for past withdrawals [see *Foti et al*., 2012, for details].

[17] In addition to the factors of Table 2, water use is affected by climatic factors, principally temperature and precipitation, that are expected to change in the future in response to rising green house gas (GHG) emissions. Estimates of these climatic variables were obtained from downscaled climate model runs for the three socioeconomic scenarios. The effects of climate change on future water use were estimated at the ASR level and are included in the DP, TF, and IR components of equation (3).

3. Principal Socioeconomic and Climatic Drivers of Water Use: Trends and Projections

3.1. Population and Income

[18] The IPCC scenarios were developed in the 1990s and do not incorporate data from the 2000 U.S. census or reflect recent economic trends. The population and income projections of the scenarios were updated for the U.S. and disaggregated to the county level for use in this and related national assessments recently performed pursuant to the Forest and Rangeland Resources Planning Act of 1974 (public law 93-378) [*U.S. Forest Service*, 2012]. The updates utilize the *U.S. Census Bureau*'s [2004] national population projection, which extends to 2050, as an update of the original A1B scenario estimate for the U.S. population (A1B being the scenario that most clearly represents a continuation of business as usual in U.S. population growth). The IPCC projections for scenarios A2 and B2 were then updated in relation to the revised A1B projection by maintaining the proportional differences among the projection paths for the U.S. of the original IPCC scenarios. To allocate county estimates to ASRs, year 2000 census tract data were used to determine the proportion of a county's population occurring in each ASR. Finally, the ASR projections were extended to 2090 using the population and income growth rates implied in the IPCC projections for the U.S. for the three scenarios.

[19] The population of the U.S. rose from 177 million people in 1960 to 294 million in 2005 along a linear trend (Figure 2). The modified A1B scenario projects a continuation of that past linear trend until about 2060, with a slight downturn thereafter, reaching a total of 499 million people in 2090 (Table 3). Scenarios A2 and B2 diverge notably from the A1B scenario beginning in about 2030, reaching populations of 644 and 404 million people in 2090 (Figure 2).

[20] Personal income in the U.S., in year 2006 dollars, rose from \$3.5 trillion in 1960 to \$10.5 trillion in 2005 (Table 3). Based on the projections of a macroeconomic model [*U.S. Forest Service*, 2012], which by and large extends the past rate of growth in real per capita income (of about 1.35% per year), total personal income with the A1B scenario reaches \$36 trillion in 2060 and \$60 trillion in 2090 (Table 3). The other scenarios anticipate lower economic growth than the A1B scenario, with total personal income reaching \$48 trillion and \$32 trillion in 2090 for scenarios A2 and B2, respectively.

3.2. Electric Energy

[21] The extent of future freshwater use in the electric energy sector depends largely on how much electricity will be produced at freshwater thermoelectric plants. Electricity (E) produced at TF plants in a given WRR and year Y, $E^{\mathrm{TF}}_{\mathrm{WRR},Y}$, was estimated as

$$E^{\mathrm{TF}}_{\mathrm{WRR},Y} = \left(\rho_{\mathrm{WRR},Y} \cdot e_{\mathrm{WRR},Y} - E^{H}_{\mathrm{WRR},Y} - E^{A}_{\mathrm{WRR},Y}\right) \frac{E^{\mathrm{TF}}_{\mathrm{WRR},2000-2005}}{E^{T}_{\mathrm{WRR},2000-2005}}, \tag{4}$$

where ρ is population, e is annual per capita electricity consumption, and E^H, E^A, and E^T are electricity produced at hydroelectric, alternative energy, and all (freshwater plus

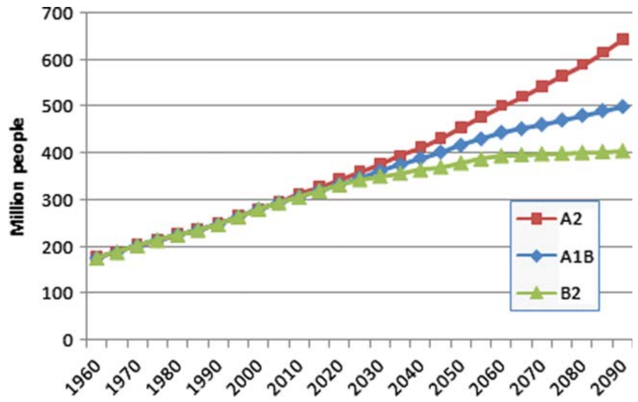

Figure 2. Past and projected population of the U.S.

Table 3. Past and Projected Levels of Drivers of Water Use in the U.S.[a]

Year	Population (Millions)	Personal Income (Billion $)[b]	Electricity Consumption (kWh/p/d)	Irrigated Area in East (ha/10^6)	Irrigated Area in West (ha/10^6)	Mean Annual Temperature (°C)	Growing Season Precipitation (cm)	Growing Season Mean ETp (mm/d)
1960	177	3476	11.6	0.8	15.0			
1965	189	4576	15.2	1.3	16.4			
1970	203	4297	20.6	2.1	17.8			
1975	214	4945	25.5	2.6	19.4			
1980	226	5582	27.6	3.3	20.2			
1985	236	6529	27.9	3.7	19.3			
1990	248	7445	30.6	4.3	19.0			
1995	265	8072	31.2	4.8	18.6			
2000	280	9802	31.7	5.8	19.1			
2005	294	10,549	32.3	6.1	18.5	11.8	44.4	5.4
2010	307	11,985	32.6	6.5	18.2	12.0	45.4	5.5
2020	334	15,579	33.0	7.2	17.9	12.5	44.3	5.5
2030	361	19,175	33.2	7.6	17.7	12.8	45.3	5.6
2040	389	23,600	33.3	7.8	17.5	13.4	42.4	5.9
2050	417	29,047	33.4	8.0	17.3	13.7	44.1	6.2
2060	444	35,750	33.5	8.1	17.1	13.6	45.2	5.9
2070	461	42,631	33.5	8.1	17.0	14.4	42.8	6.3
2080	480	50,723	33.5	8.2	16.9	14.3	44.8	6.2
2090	499	60,026	33.5	8.2	16.8	15.0	43.6	6.4

[a]Population and income are for the A1B scenario. Electricity consumption is for the entire U.S., not just the coterminous U.S. The three weather variables are for the A1B-CGC scenario-model combination. Weather variables give 5 year averages. The dotted line separates past estimates at 5 year intervals from projections at 10 year intervals.
[b]Year 2006 dollars. Estimates for past years are from the Bureau of Economic Analysis.

saltwater) thermoelectric plants, respectively. $\rho \cdot e$ gives total electricity production (E). The term in parentheses gives E^T for a given year. E^A represents a variety of plants using renewable energy sources including solar, wind, and geothermal energy and plants burning wood and other biomass or municipal waste. The proportion of future thermal production that will occur at freshwater, as opposed to saltwater, plants was assumed to remain at the average proportion for 2000 and 2005 (equation (4)) as estimated from the USGS water use data. An underlying assumption of equation (4) is that total national production equals consumption, although this equality need not hold at smaller scales.

[22] The growth in per capita U.S. electric energy use has slowed greatly in recent years (Table 3). Future levels of e at the WRR scale were modeled using the approach of equation (2) and coefficients of Table 4 with g set at the 1990–2005 U.S. annual growth rate. Applying the same coefficients to all WRRs essentially assumes that WRRs that have produced a disproportionate share of the U.S. electricity supply will continue to do so.

[23] From 1960 to 2005, there was relatively little growth in production at hydroelectric and other renewable plants, such that the additional production needed to satisfy rising demand was met at thermoelectric plants (Table 5). However, as indicated in a recent Department of Energy (DOE) Annual Energy Outlook [*Energy Information Administration (EIA)*, 2010], production at other renewable plants is expected to rise sharply, from 61 billion kWh in 2005 to 589 billion kWh in 2035 (Table 5). Extrapolating the DOE's projections beyond 2035 using the coefficients of Table 4 shows the U.S. production at other renewable plants reaching 765 billion kWh in 2090 (Table 5).

[24] Given these assumptions, electricity production at freshwater thermoelectric plants is projected to remain fairly flat from 2005 to 2015 (in response to the depressed economy and the rapid growth in production at other renewable plants) and then grow along a nearly linear projection to 2090, assuming the A1B population projection (Table 5). As explained in a later section, climate change is projected to increase electricity per capita consumption and therefore freshwater thermoelectric production beyond the levels reported in Table 5.

3.3. Irrigated Area

[25] Irrigated area in the west (WRRs 10–18), where the majority of irrigation occurs, grew rapidly from 1960 to 1980, then dropped from 1980 to 1995, with little net change between 1995 and 2005 (Table 3). The drop occurred as farmers sold some of their land or water to cities, industries, and rural domestic users, and as pumping

Table 4. Extrapolation Coefficients g (Growth Rate) and d (Decay Rate) (see Equation (2))

	East		West	
	g	d	g	d
Driving factors				
Total kWh/capita	0.0037	−0.0500	0.0037	−0.0500
Other renewable energy kWh	0.0265	−0.0300	0.0265	−0.0300
Irrigated acres	0.0253	−0.0350[a]	−0.0021	−0.0100[b]
Efficiency factors				
DP	−0.0066	−0.0300	−0.0035	−0.0300
IC	−0.0369	−0.0350	−0.0578	−0.0420
TF	−0.0176	−0.0200	−0.0106	−0.0200
IR	0.0000	0.0000	−0.0044	−0.0250
LS	−0.0069	−0.0400	−0.0218	−0.0400
AQ	0.0540	−0.0500	0.0804	−0.1000

[a]Exceptions: WRRs 3, 8, and 9 set at −0.09, −0.08, and −0.07, respectively.
[b]Exception: WRR 10 set at −0.05.

Table 5. Past and Projected U.S. Electricity Production Given the A1B Population Projection in the Absence of Climate Change, billion kWh/yr[a]

Year	Fresh Thermal	Salt Thermal	Hydropower	Other Renewable
1960	447	161	146	0
1965	629	233	194	0
1970	942	342	248	0
1975	1161	539	303	0
1980	1384	626	276	0
1985	1621	507	296	0
1990	1909	578	298	0
1995	2081	594	310	44
2000	2292	630	271	49
2005	2545	622	262	61
2010	2564	661	271	191
2015	2562	663	300	349
2020	2654	690	300	413
2025	2731	713	302	493
2030	2831	741	302	550
2035	2943	772	303	589
2040	3070	806	302	616
2050	3324	870	302	662
2060	3584	932	302	699
2070	3732	970	302	727
2080	3909	1016	302	748
2090	4083	1061	302	765

[a]This table is for the entire U.S., not the coterminous U.S. Estimates for 1960–2005 are from USGS water use circulars when available and otherwise from DOE. Estimates for hydropower and other renewable sources for 2010–2035 are from DOE's 2010 Annual Energy Outlook; estimates beyond 2035 are computed by extrapolation. In keeping with the DOE release, the estimates ignore the possibility of hydrokinetic energy. The dotted line separates past estimates from projections.

costs, crop prices, and government incentive programs caused marginal lands to be removed from irrigation. Meanwhile, irrigated area in the east (WRRs 1–9) grew continuously from 1960 to 2005, as farmers have increasingly used irrigation water to supplement precipitation during dry times, in order to reduce variability in yields and maintain product quality [*Moore et al*., 1990].

[26] Irrigated area responds to a complex mixture of factors: those that affect total agricultural area (e.g., land prices, crop yields, agricultural product markets, agricultural policies, and subsidies) and those specific to irrigation (e.g., energy prices, irrigation technologies, and demand for water in other uses). In light of the difficulty of accounting for all these factors, irrigated area was projected at the WRR scale by extrapolating from past trends using equation (2) with the extrapolation coefficients listed in Table 4. No attempt was made to develop separate estimates for the different emission scenarios. The WRR projections were apportioned to ASRs using the 1995 eight-digit basin water withdrawal data from the USGS.

[27] Irrigated area in the west was projected to continue the downward trend begun in the early 1980s, dropping from 18.5×10^6 ha in 2005 to 16.8×10^6 ha in 2090 (Table 3). In the east, irrigated area is projected to continue to increase, at a decreasing rate, from 6.1×10^6 ha in 2005 to 8.2×10^6 ha in 2090. Total U.S. irrigated area is projected to peak in about 2040 at 25.3×10^6 ha. Meeting the renewable fuel standard goals would increase irrigated area slightly [*Foti et al*., 2012].

3.4. Climate

[28] For this study, a subset of the available GCMs was selected to estimate the effect of the socioeconomic scenarios on future climate [*Joyce et al*., 2013]. The three scenarios were each modeled with three climate models, creating nine different scenario-model combinations. The CGCM3.1MR (hereafter CGC), CSIROMK3.5 (hereafter CSIRO), and MIROC3.2MR (hereafter MIROC) models were paired with the A1B and A2 scenarios (Table 6). Climate of the B2 scenario was projected with the CGCM2 (hereafter also CGC), CSIROMK2 filtered (hereafter also CSIRO), and HADCM3 (hereafter Hadley) models. See *Joyce et al*. [2013] for full citations and descriptions of the original climate model data.

[29] For each scenario-model combination, the downscaled and bias-corrected projections of monthly precipitation, minimum temperature, and maximum temperature for 1961–2100 were prepared for this and related studies by *Joyce et al*. [2013], available at http://www.fs.fed.us/rm/data_archive/dataaccess/US_ClimateScenarios_grid_A1B_A2_PRISM.shtml. As *Joyce et al*. [2011] describe, the downscaling for each of the nine scenario-model combinations was performed using the ANUSPLIN software [*Price et al*., 2006] to approximately a 10 km grid for the U.S. The bias correction was performed using data at the 4 km grid scale from the PRISM data set [*Daly et al*., 1994]. The estimates of potential evapotranspiration (ETp) were computed from the downscaled estimates for temperature using a modification of Penman's equation by *Linacre* [1977]. The lack of downscaled data on other variables precluded the use of the original Penman equation; however, as reported in section 6.5, we subsequently used the Penman equation with separately downscaled data for two of the nine combinations to evaluate the sensitivity of our estimates of withdrawal to the ETp inputs.

[30] The projections indicate that the average U.S. temperature (the midpoint between the minimum and maximum temperatures) will increase from 11.8°C for 2005 to from 13.9°C to 16.5°C for 2080 depending on which scenario-model combination is used. However, the projections are not in agreement about the future direction of precipitation; average annual precipitation is projected to change from 77 cm for 2005 to from 58 to 83 cm for 2080 depending on the scenario-model combination. Of course, these national estimates mask an even greater variation for smaller areas such as ASRs.

Table 6. GCMs Used to Model the Three Scenarios

A1B	A2	B2
CGCM3.1MR[a]	CGCM3.1MR[a]	CGCM2MR[a]
CSIROMK3.5[b]	CSIROMK3.5[b]	CSIROMK2 filtered[b]
MIROC3.2MR[c]	MIROC3.2MR[c]	HADCM3[d]

[a]Developed by the Canadian Center for Climate Modeling.
[b]Developed by the Commonwealth Scientific and Industrial Research Organization in Australia.
[c]Developed by a consortium headed by the Center for Climate System Research at the University of Tokyo.
[d]Developed by the Hadley Centre for Climate Prediction and Research in England.

Table 7. Past and Projected Efficiency Factors for the East Assuming No Future Climate Change[a]

Year	Φ^{DP} (L/p/d)	Φ^{IC} (L/\$1000/d)[b]	Φ^{TF} (L/kWh)	Φ^{IR} (cm)	Φ^{LS} (L/p/d)	Φ^{AQ} (L/p/d)
1960	291	48		31		
1965	315	42		57		
1970	356	48		39		
1975	369	41		45		
1980	369	38		54		
1985	390	25	132	39		
1990	396	21	117	42	18	33
1995	401	19	107	42	18	31
2000	390	15	98	43	17	38
2005	376	13	92	41	16	72
2010	370	12	87	41	16	77
2020	355	9	77	41	16	102
2030	344	8	70	40	15	121
2040	336	7	65	40	15	134
2050	330	6	61	40	15	142
2060	326	6	58	40	15	148
2070	323	6	56	39	15	152
2080	321	6	54	39	15	154
2090	319	6	53	39	15	155

[a]The dotted line separates past estimates at 5 year intervals from projections at 10 year intervals. Past withdrawal estimates are from the USGS water use circulars.
[b]Year 2006 dollars.

4. Water Use Efficiency: Trends and Projections

[31] Water withdrawal efficiency (Φ, equation (1)) plays a key role in the approach used here to project future water use. The efficiency factor projections presented in this section assume no future change in climate. Effects of climate change are discussed in a subsequent section. Findings are summarized here for the east and west, but note that to project future water use the efficiency factors were estimated separately for each WRR using the east-wide and west-wide extrapolation coefficients.

4.1. Domestic and Public Use

[32] During most of the latter half of the twentieth century, daily per capita domestic and public water withdrawals (Φ^{DP}) in the U.S. steadily increased, rising from 341 L in 1960 to 462 L in 1990. Since 1990 nationwide Φ^{DP} has remained at about 450 L, but this stability masks an important regional difference. In the east, Φ^{DP} peaked in 1995 at 401 L and then dropped to 390 L in 2000 and 376 L in 2005 (Table 7), whereas in the west the trend in Φ^{DP} is still uncertain, as it fluctuated in the vicinity of 570 L from 1985 to 2005 (Table 8). The projected growth rate (g) in the east was based on the change from 1995 to 2005. It is assumed that the rate in the west will also decline, but at a lesser rate. Given the g and d rates of Table 4, Φ^{DP} is projected in 2090 to reach 319 L in the east and 534 L in the west (Tables 7 and 8).

4.2. Industrial and Commercial Use

[33] Because of the great variety of outputs of the industrial and commercial sectors, relating water use to units of physical output is unrealistic. Instead, an economic measure of total output, personal income, was used. Withdrawal per day per \$1000 of total real personal income (Φ^{IC}) declined steadily from 1960 to 2005 (Tables 7 and 8). This drop is largely attributable to changes in the type and quantity of industrial and commercial outputs produced, such as a shift from water intensive manufacturing and other heavy industrial activities to service-oriented businesses, and to enhanced efficiency of water use, especially as firms have increased their reuse of withdrawn water in the effort to reduce costs and lower effluent releases [*David*, 1990; *Dupont and Renzetti*, 2001; *Renzetti*, 1992]. The most recent data show that the rate of decrease in Φ^{IC} has slackened somewhat (Tables 7 and 8).

[34] The 2005 Φ^{IC} rates were 13 L in the east and 8 L in the west in 2006 dollars (Tables 7 and 8). The reasons for past declines are likely to continue to play a role, suggesting that recent past trends are a good indication of future changes. It is assumed here that the annual rate of change from 1995 to 2005 (g in Table 4) will be attenuated gradually (d in Table 4), as the use rate approaches a minimum needed for operations, resulting in rates of 6 L in the east and about 3 L in the west in 2090 (Tables 7 and 8). Meeting the renewable fuel standard goals would increase the industrial and commercial withdrawals (for processing nonpetroleum liquid fuels) [*Foti et al.*, 2012].

4.3. Thermoelectric Use

[35] About 90% of the electric energy produced in the U.S. is currently generated at thermoelectric power plants, most of which use heat from nuclear fission or burning of fossil fuels (principally coal, natural gas, and oil) to produce steam to turn turbines [*EIA*, 2009]. Most of these plants require substantial amounts of water for condensing steam as it leaves the turbines, plus some additional water for equipment cooling and emission scrubbing. Water-cooled plants use either a once-through or closed-loop cooling system. In a once-through system, a large volume of water is withdrawn, used for making and condensing steam and other purposes, and then returned to the source, at a higher temperature. Closed-loop systems withdraw much less water than once-through systems and recycle that water, sending the condensed and cooling water to a cooling tower or pond for later reuse. Ongoing withdrawals at closed-loop systems are needed to make up for

Table 8. Past and Projected Efficiency Factors for the West Assuming No Future Climate Change[a]

Year	Φ^{DP} (L/p/d)	Φ^{IC} (L/\$1000/d)[b]	Φ^{TF} (L/kWh)	Φ^{IR} (cm)	Φ^{LS} (L/p/d)	Φ^{AQ} (L/p/d)
1960	469	28.7		76		
1965	496	23.2		92		
1970	474	24.4		93		
1975	490	23.5		95		
1980	552	25.0		94		
1985	559	14.7	51	90		
1990	591	12.9	47	89	66	38
1995	544	14.2	46	89	60	74
2000	587	11.1	45	85	58	122
2005	581	7.8	41	82	47	161
2010	576	7.1	39	82	45	191
2020	564	5.0	35	79	39	238
2030	555	4.0	32	77	35	257
2040	549	3.5	30	75	33	265
2050	544	3.2	28	74	31	269
2060	541	3.0	27	73	30	271
2070	538	2.9	26	72	30	271
2080	536	2.8	25	72	30	271
2090	534	2.8	25	71	29	271

[a]The dotted line separates past estimates at 5 year intervals from projections at 10 year intervals. Past withdrawal estimates are from the USGS water use circulars.
[b]Year 2006 dollars.

evaporation of cooling water and for the water used to flush away minerals and sediment that accumulate in the cooling water.

[36] Freshwater withdrawals per kWh produced (Φ^{TF}) have been falling, though at a declining rate, in both the east and west (Tables 7 and 8). The reasons for past declines (especially the movement from once-through to recycling plants) are likely to continue to play a role, suggesting that recent past trends are a good indication of future changes. It is assumed here that the annual rate of change will gradually diminish from the 1985–2005 base, in keeping with past declines in the growth rate. The decay rate would necessarily be greater in the west, which has already reduced withdrawals per kWh to a low level, than in the east where large improvements are still possible (Table 4). Withdrawals per kWh are projected to decrease from 92 L in 2005 to 53 L in 2090 in the east (Table 7) and correspondingly from 41 to 25 L in the west (Table 8). These estimates ignore the water that would be needed if carbon capture were to be required at coal-fired plants [*National Energy Technology Laboratory (NETL)*, 2008].

4.4. Irrigation

[37] Since 1985, the water withdrawal efficiency rate (annual irrigation depth including conveyance losses, Φ^{IR}) in the east has hovered around 42 cm (Table 7), whereas in the west the irrigation depth has fallen from 95 cm in 1975 to 82 cm in 2005 (Table 8). The rate is lower in the east because of the east's higher precipitation rates and the prevalence in the east of more efficient irrigation methods, principally sprinklers. The lack of improvement in the east is probably due to the fact that more efficient methods are already in common use there. The improving irrigation efficiency in the west is largely a response to a gradual shift to more efficient irrigation technology induced by such factors as the waning of the era of publicly funded dam and canal construction, higher prices for water from publicly funded projects, and increasing ground water pumping lifts [*Anderson and Magleby*, 1997; *Marques et al.*, 2005; *Moore et al.*, 1990]. In the east, future withdrawal per unit area is assumed to decrease only slightly from the mean 1985–2005 rate (Table 7). In the west, withdrawal per unit area is projected to continue falling (Table 4), reaching 71 cm in 2090 (Table 8).

4.5. Livestock and Aquaculture

[38] Water withdrawals for livestock have been estimated by the USGS largely based on the 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, seepage, and refresh rate. Because estimates of future stock numbers and pond areas were not available for projecting future livestock and aquaculture water use, human population was used as the demand unit based on the assumption that population is an underlying determinant of demand for livestock and fish products, with past trends in per capita withdrawals capturing changes in tastes as well as changes in water use efficiency.

[39] Livestock withdrawal per capita (Φ^{LS}) has been dropping at least since 1990 (when the USGS data first allow clear separation between livestock and aquaculture) (Tables 7 and 8), presumably because of improved efficiency of water use and changing consumer tastes [*Haley*, 2001]. Using extrapolation with the coefficients listed in Table 4, the daily per capita withdrawal rates are projected to drop in the east from 16 L in 2005 to 15 L in 2090 (Table 7) and in the west from 47 L in 2005 to 29 L in 2090 (Table 8).

[40] Aquaculture withdrawal per capita (Φ^{AQ}) has been rising since 1990 (Tables 7 and 8), as aquaculture has become ever more prevalent. Using extrapolation with the coefficients listed in Table 4, the daily per capita withdrawal rates are projected to rise in the east from 72 L in 2005 to 155 L in 2090 (Table 7) and in the west from 161 L in 2005 to 271 L in 2090 (Table 8). Note that refresh

rates differ widely among locations depending on the species grown.

5. Climate Change Effects

[41] Water use, especially in some sectors, is sensitive to climatic factors. The effects examined here are those of temperature (and therefore evapotranspiration) and precipitation on agricultural irrigation and landscape watering and of temperature on demand for indoor air cooling and thus on electricity production at thermoelectric plants. These effects are summarized below. In general, they take the form:

$$\Delta W = U \cdot \Delta \Phi, \tag{5}$$

where U is a driver of water use, $\Delta\Phi$ is the change in efficiency of water use attributable to climate change, and ΔW is the change in withdrawal attributable to climate change of equation (1).

5.1. Effects on Crop Irrigation

[42] The net irrigation amount per unit area ($\Phi^{\mathrm{IR}}_{\mathrm{net}}$) is often defined as

$$\begin{aligned} \Phi^{\mathrm{IR}}_{\mathrm{net}} &= k_c \mathrm{ETp} - P' && \text{if } k_c\mathrm{ETp} > P', \\ \Phi^{\mathrm{IR}}_{\mathrm{net}} &= 0 && \text{otherwise,} \end{aligned} \tag{6}$$

where ETp is potential evapotranspiration, P' is effective precipitation [*Döll*, 2002], and k_c is a crop-specific dimensionless constant. k_cETp represents crop water demand, and P' is the part of that demand that does not need to be met by irrigation (note that this definition of effective precipitation is different from a common understanding of the term as the portion of precipitation that produces runoff). In this formulation, it is assumed that irrigation fully satisfies crop water demand, and thus that water is not a limiting factor in plant growth. Because we are not differentiating among crops, k_c is set to 1.

[43] The change in $\Phi^{\mathrm{IR}}_{\mathrm{net}}$ with a change in climate ($\Delta\Phi^{\mathrm{IR}}_{\mathrm{net}}$) for the situation where precipitation is inadequate to satisfy crop water demand is

$$\begin{aligned} \Delta\Phi^{\mathrm{IR}}_{\mathrm{net}} &= \Phi^{\mathrm{IR}}_{\mathrm{net},2} - \Phi^{\mathrm{IR}}_{\mathrm{net},1} \\ &= \left(\mathrm{ETp}_2 - P'_2\right) - \left(\mathrm{ETp}_1 - P'_1\right) \\ &= \left(\mathrm{ETp}_2 - \mathrm{ETp}_1\right) + \left(P'_1 - P'_2\right), \end{aligned} \tag{7}$$

where 1 and 2 indicate time before and after some change in climate, respectively. The change in irrigation withdrawal attributable to climate change (ΔC^{IR}) is then

$$\Delta W^{\mathrm{IR}} = U^{\mathrm{IR}} \cdot \frac{\Delta\Phi^{\mathrm{IR}}_{\mathrm{net}}}{\gamma}, \tag{8}$$

where U^{IR} is the irrigated acres, and γ is the irrigation efficiency (computed from USGS estimates for 1990 and 1995 as irrigation consumptive use divided by irrigation withdrawal). The two terms of the $\Phi^{\mathrm{IR}}_{\mathrm{net}}$ difference in equation (7), representing the two identified influences of climate change on irrigation requirement, are considered in the following subsections. The direct effect of CO_2 increases on irrigation demand is ignored here (for a discussion of this topic see *Foti et al*. [2012]).

5.1.1. ETp Effect

[44] Because ETp is estimated based on the downscaled temperature projections and temperature is increasing everywhere, ETp is also everywhere increasing. For the U.S. as a whole, growing season (April–September) ETp is projected to increase from about 5.3 mm/d in 2005 to from 6.0 to 7.6 mm/d across the scenario-model combinations. Assuming, as mentioned above, that irrigation fully meets crop water demand, irrigation would be needed to make up for this deficit, all else equal.

5.1.2. Precipitation Effect

[45] The variable P' is the portion of total precipitation (P) that is useable by the plant. The P'/P proportion depends on the precipitation rate and the ability of the soil to hold additional water, which vary extensively across space and time, making accurate estimates at a regional scale especially difficult. A simple approximation is used here, the U.S. Department of Agriculture Soil Conservation Method as described by *Smith* [1992, p. 21; see also *Döll*, 2002] where, in terms of monthly mean depth in centimeters, effective precipitation is:

$$\begin{aligned} P' &= P(12.5 - 0.2P)/12.5 && \text{for } P < 25\mathrm{cm/month}, \\ P' &= 12.5 + 0.1P && \text{for } P \geq 25\mathrm{cm/month}. \end{aligned} \tag{9}$$

[46] Accordingly, the proportion of a change in P that is available to meet crop water demands varies linearly with P from 1.0 at very low monthly P to 0.2 at P approaching 25 cm/month and is then constant at 0.1 at P of at least 25 cm/month.

[47] Given equation (9), the change in P' for a discrete change in P from P_1 to P_2 of equation (7) is

$$\begin{aligned} P'_1 - P'_2 &= (P_1 - P_2) + 0.016\left(P_2^2 - P_1^2\right) && \text{for } P_1 < 25\mathrm{cm/month}, \\ P'_1 - P'_2 &= 0.1(P_1 - P_2) && \text{for } P_1 \geq 25\mathrm{cm/month}. \end{aligned} \tag{10}$$

[48] For implementation of this approach to estimating P', we assume a 6 month growing season (from April to September) and compute monthly P as the mean monthly P over the growing season (a simplification that may overestimate P' in some areas where P is unevenly distributed over the growing season). Among the ASRs, the maximum monthly P in 2005 (the base year for computing precipitation changes) is about 18 cm. Thus, $\Delta P'/\Delta P$ remains within the range from 0.45 to 1.

5.2. Effects on Landscape Irrigation

[49] The plants used in landscaping (perennials including grass, forbs, shrubs, and trees, as well as annuals such as flowers and vegetables) differ widely in their water use requirements. As temperatures increase, the growing season for perennial species may lengthen, whereas for some annual species it may shorten. The additional biomass production that is expected with higher CO_2 levels may be unnecessary and thus consciously avoided for some species (e.g., irrigated cool season grasses), resulting in water

Table 9. Data for Estimating η (See Equations (12) and (13))

WRR	DP Annual Withdrawal (L/p/d) (1)	Proportion of Withdrawal Used Outdoors (ω) (2)	DP Annual Withdrawal Used Outdoors (L/p/d) (3)	Mean Effective P April–September (cm) (4)	Mean Annual ETp (cm) (5)
1	324	0.07	24	51	79
2	370	0.03	12	52	100
3	410	0.12	51	56	136
4	326	0.10	32	45	81
5	317	0.08	24	53	105
6	348	0.08	26	53	119
7	361	0.17	63	49	91
8	471	0.14	64	56	133
9	329	0.14	46	38	77
10	480	0.33	160	34	115
11	453	0.28	126	41	141
12	627	0.21	132	42	156
13	729	0.26	186	23	181
14	586	0.44	256	17	139
15	657	0.32	212	13	228
16	693	0.48	334	12	157
17	472	0.34	161	22	104
18	593	0.44	260	8	177

savings, but welcomed for others (flowers and vegetables). This complex situation makes the effect of temperature and precipitation changes on overall landscape water use at least as difficult to project as that for agricultural crops.

[50] Lacking comprehensive data on area irrigated, we took an indirect approach to estimating the effect of changing precipitation or ETp on domestic and public withdrawal. The approach relies on the recent relation of per capita withdrawal to precipitation or ETp, estimated from variation across space at the WRR scale, to indicate the future change in per capita withdrawal with changing precipitation or ETp. The estimated change in per capita withdrawal per unit change in precipitation or ETp was then multiplied by the future changes in precipitation or ETp to estimate future change in per capita domestic and public withdrawal. The total impact of climate change on domestic and public water use (ΔW^{DP}) is the sum of two effects:

$$\Delta W^{\mathrm{DP}} = \Delta W^{\mathrm{DP},P'} + \Delta W^{\mathrm{DP,ETp}}. \qquad (11)$$

[51] These effects are explained more fully in the following subsections.

5.2.1. Precipitation Effect

[52] The effect of a change in P' on domestic and public withdrawal ($\Delta W^{\mathrm{DP},P'}_{\mathrm{ASR},Y}$) in liter days (L/d for a year) for a given ASR and future year (Y) was modeled as population (U^{DP}) times change in per capita withdrawal due to the change in P' ($\Delta\Phi^{\mathrm{DP},P'}$) as follows:

$$\Delta W^{\mathrm{DP},P'}_{\mathrm{ASR},Y} = U^{\mathrm{DP}}_{\mathrm{ASR},Y} \cdot \Delta\Phi^{\mathrm{DP},P'}_{\mathrm{ASR},Y} = U^{\mathrm{DP}}_{\mathrm{ASR},Y} \cdot \eta^{P'} \cdot \Delta P'_{\mathrm{ASR},Y}, \qquad (12)$$

where $\eta^{P'}$ is the change in domestic and public L/p/d withdrawn for a 1 cm change in P', and $\Delta P'$ is the change in P' from 2005 to year Y.

[53] The variable η^{P} was computed by regressing, at the WRR scale, the annual per capita domestic and public water withdrawal used outdoors in L/p/d (Table 9, column (3)) on mean growing season (April–September) P' in cm (Table 9, column (4)). The slope of the linear regression, -5.358, gives η^{P} (R^2=0.85). For the regression, growing season P' was estimated using equation (9), with growing season P taken from PRISM data [*Daly et al.*, 1994] as mean April–September precipitation for 10 recent years spanning the period represented by most of the city monthly delivery data, mentioned below. And the annual per capita domestic and public withdrawal used outdoors was estimated as total annual domestic and public withdrawal [*Kenny et al.*, 2009] times ω, the proportion of that withdrawal used outdoors. The variable ω was computed as $1-12\,b$ where b is the mean monthly proportion of the annual domestic and public withdrawal used in January and February, under the assumption that water is used only indoors during those 2 months (Table 9, column (2)). The variable b was based on a survey of 232 cities across the U.S. (about 13 cities per WRR on average), each providing from one to four recent years of monthly water delivery data [*Foti et al.*, 2012].

5.2.2. ETp Effect

[54] The procedure for estimating the change in domestic and public water use for a change in ETp is similar to that used for a change in precipitation. The effect of a change in ETp on withdrawal in liter-days for a given ASR and future year ($\Delta W^{\mathrm{DP,ETp}}_{\mathrm{ASR},Y}$) was modeled as follows:

$$\Delta W^{\mathrm{DP,ETp}}_{\mathrm{ASR},Y} = U^{\mathrm{DP}}_{\mathrm{ASR},Y} \cdot \Delta\Phi^{\mathrm{DP,ETp}}_{\mathrm{ASR},Y} = U^{\mathrm{DP}}_{\mathrm{ASR},Y} \cdot \eta^{\mathrm{ETp}} \cdot \Delta\mathrm{ETp}_{\mathrm{ASR,Y}}, \qquad (13)$$

where η^{ETp} is the change in domestic and public L/p/d withdrawn for a 1 cm change in ETp, and ΔETp is the change in ETp from 2005 to year Y. The variable η^{ETp} was computed by regressing, at the WRR scale, the annual per capita domestic and public water withdrawal in L/p/d (Table 9, column (1)) on mean annual ETp in centimeters (Table 9, column (5)). Annual ETp was estimated from the

PRISM temperature data, as described above. The slope of the regression line, 2.946, gives η^{ETp} (R^2=0.73).

5.3. Effects on Thermoelectric Water Use

[55] The primary effect of climate change on thermoelectric energy production is expected to be the impact of temperature increases on space cooling. As characterized by *Sailor and Pavlova* [2003], there are both short-term and long-term effects of temperature increases on electricity used for space cooling. In the short term, residents and businesses decide on a daily basis whether or not to use their air conditioners, and in the long term those without air conditioners decide whether or not to install them. Because most commercial establishments and office buildings already have air conditioning units, it is assumed that only short-term effects are relevant to the commercial sector, but for the residential sector both short-term and long-term effects are relevant. Industrial electricity consumption is much less sensitive to temperature than are residential and commercial uses [*Amato et al.*, 2005; *Elkhafif*, 1996; *Sailor and Muñoz*, 1997] and is ignored here. Thus, two factors were estimated, one for commercial use that includes only a short-term effect (M^{comm}) and the other for residential use that includes a combined short-term and long-term effect (M^{resid}). Because of the limited published information available on these effects, the estimates were performed at the WRR level.

[56] Both the short-term and long-term effects of temperature on per capita electricity consumption vary across the U.S. [*Sailor*, 2001; *Sailor and Pavlova*, 2003]. Short-term effects vary spatially due to the differences in climate and also due to the available energy sources (as illustrated by the case of the state of Washington, which, unlike other states, also relies largely on electricity for space heating). Long-term effects vary because air conditioning is already routine in some warm areas (market saturation exceeds 90% in parts of the southeastern U.S.) but becomes increasingly less common to the north. Opportunities for increasing market saturation are obviously greater in areas not already relying heavily on air conditioning.

[57] Because of the regional differences, studies that have applied consistent methods over a mixture of conditions are most useful for estimating large-scale impacts. Estimates of short-term effects produced here rely on the results of *Sailor* [2001]. Separately for residential and commercial uses, the relation of temperature to change in electricity use among the states in Sailor's study was expanded to all states using data on past (1971–2000) state temperatures. These state-level relations were then matched to WRRs based on the proportion of a WRR falling in respective states. To reflect the nonlinear nature of the relations, the residential and commercial equations for short-term effects are of the form:

$$M^{ST} = \Delta T x_1 + \Delta T^2 x_2, \tag{14}$$

where ΔT is the change in annual temperature in degrees Celsius, M^{ST} is the proportion increase in electricity consumption due to short-term effects, and x_1 and x_2 are the regression coefficients (listed in Table 10). As would be expected, the short-term effect is greatest across the southern tier of the U.S. (WRRs 3, 8, 12, 15, and 18) and relatively low in northern areas such as New England (WRR 1).

Table 10. Coefficients for Computation of the Change in Thermoelectric Energy Per Capita Consumption With Future Climate Change (See Equations (14) and (15))

	Residential			Commercial	
WRR	x_1	x_2	x_3	x_1	x_2
1	0.136	0.023	2.63	0.592	0.044
2	0.633	0.113	1.62	0.903	0.065
3	3.053	0.451	1.06	1.710	0.123
4	0.255	0.070	1.90	0.721	0.058
5	0.763	0.156	1.67	1.045	0.081
6	1.624	0.281	1.36	1.279	0.093
7	0.543	0.097	1.90	0.709	0.055
8	2.294	0.399	1.06	1.487	0.109
9	0.085	0.015	2.12	0.345	0.027
10	0.265	0.046	1.36	0.675	0.049
11	1.494	0.233	1.36	1.136	0.084
12	2.361	0.224	1.06	1.011	0.074
13	1.630	0.192	1.06	1.030	0.076
14	0.085	0.015	1.67	0.730	0.054
15	2.096	0.364	1.06	1.429	0.103
16	0.189	0.033	1.47	0.825	0.061
17	−1.117	0.083	2.33	0.289	0.091
18	1.589	0.226	1.63	2.161	0.124

[58] *Sailor and Pavlova* [2003] estimated the short-term and long-term changes in residential electricity consumption for 12 U.S. cities. Using this information, the ratio of total percent increase to short-term percent increase (x_3) was computed, and the ratios were then extended to the 18 WRRs by selecting the cities or groups of cities that were considered most representative of the WRRs. As seen in Table 10, the long-term effect is very small in southern, hotter areas (e.g., WRRs 3, 13, 14, and 15) and rises progressively as one moves north, with the exception of WRR 17, which includes the state of Washington and is therefore a special case. The total (short-term plus long-term) proportional increase in electricity consumption in the residential sector with a change in temperature is

$$M^{resid} = x_3 M^{ST,resid}. \tag{15}$$

[59] The effect of a temperature change on thermoelectric withdrawals (ΔW^{TF}) is then

$$\Delta W^{TF}_{ASR,Y} = \varepsilon_{ASR} \left[U^{TF}_{WRR,Y} \cdot e_{WRR,Y} \left(M^{resid}_{WRR} + M^{comm}_{WRR} \right) \Phi^{TF}_{WRR,Y} \right], \tag{16}$$

where U^{TF} is population, e is electricity consumption per capita in the absence of climate change, Φ^{TF} is withdrawal per kWh produced at thermoelectric plants, and ε_{ASR} is the proportion of fresh thermal withdrawal in the WRR that occurred in the ASR in 1995, the last year for which we have USGS water use data by watershed. As indicated, these estimates rely on a good deal of spatial extrapolation; this would be of greater concern if the overall effect on water use were larger than, as seen below, it was found to be.

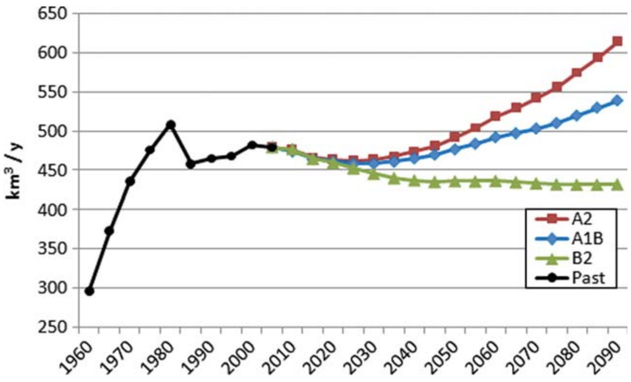

Figure 3. Past and projected annual water withdrawal in the U.S., given future population and income for three scenarios, no future change in climate.

6. Past and Projected Water Withdrawals

[60] To provide some context for considering the projections, past levels of withdrawal are first summarized. Next, the effect on withdrawals of population and income increases alone are presented, followed by the effects of future climate change. Finally, the combined effects of population, income, and future climate change are presented.

6.1. Past Withdrawals

[61] Combining across all water use sectors, total U.S. freshwater withdrawals rose by 72% from 1960 to 1980 but remained relatively stable from 1985 to 2005 (Figure 3). The small change in total withdrawals from 1985 to 2005 is remarkable in light of the 25% rise in population during that period (from 236 million to 294 million persons). Note that the dramatic drop in total withdrawal from 1980 to 1985 may be at least partly the result of weather and economic fluctuations and of a change in USGS procedures for estimating water use [*Brown*, 2000; *Solley et al*., 1988].

[62] These trends in total withdrawal, rapid rise followed by relative stability, are not shared by all water uses. The rise from 1960 to 1980 was due mainly to IR and TF uses (Figure 4). Meanwhile, the relative stability from 1985 to 2005 is attributable not only to the ending of the rapid rise in IR and TF withdrawals but also to the fact that declines in IR and IC uses roughly balanced the combined increases in TF, DP, and LA uses [see also *Kenny et al*., 2009].

[63] The TF and IR sectors have consistently dominated national withdrawals, each with annual levels of roughly 185 km^3 since 1985 (Figure 4). The IC and the DP sectors form an intermediate group, with recent annual withdrawals of about 45 km^3. Finally, annual LA withdrawals reached 14 km^3 in 2005, with recent increases caused by growth of aquaculture.

[64] In the following subsections, the very modest (<1%) effect on withdrawal of meeting the renewable fuel standards specified in the Energy Independence and Security Act of 2007 [*Foti et al*., 2012] is included in all cases.

6.2. Effects of Projected Levels of Population, Income, and Water Use Efficiency Assuming No Future Climate Change

[65] We first examine the effects of population and income growth on withdrawals assuming no future change in climate. Water use was projected for three alternative specifications of future population and income in the U.S. corresponding to the A1B, A2, and B2 scenarios. Recall that projections for the DP, IC, TF, and LA sectors are tied to population projections and projections for the IC sector are also tied to income projections.

[66] Assuming the A1B population and income projections, which incorporate the U.S. Census Bureau's 2000 projection of future U.S. population levels, little change in total U.S. withdrawals is projected over the next 50 years. Annual withdrawals are projected to drop gradually from 480 km^3 in 2005 to 459 km^3 in 2025 and increase gradually thereafter, reaching 493 km^3 in 2060, for a net increase from 2005 to 2060 of 3% (Figure 3). The gradual increase of the 2025–2060 period is projected to continue after 2060 with total withdrawals reaching 540 km^3/yr in 2090, for a net increase from 2005 to 2090 of 13%.

[67] In contrast to the long-term net increase in total withdrawal, total withdrawal per capita with the A1B scenario is projected to fall continuously, from 4470 L/p/d in 2005 to 3040 L/p/d in 2060 to 2965 L/p/d in 2090

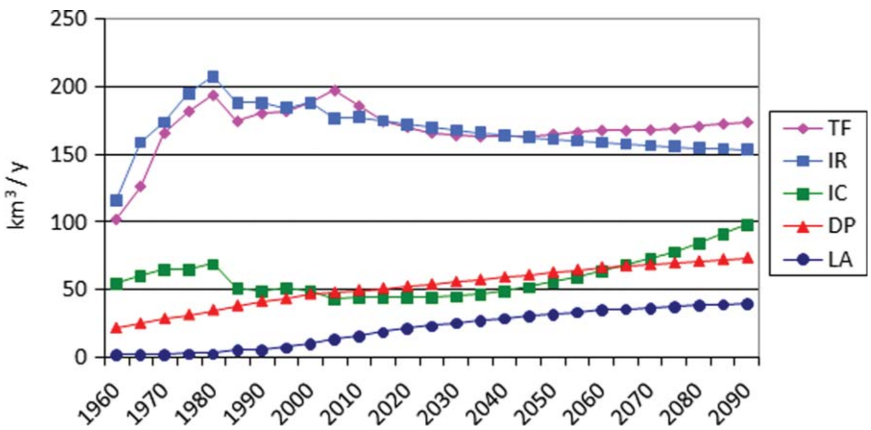

Figure 4. Past and projected annual withdrawal in the U.S. by water use sector, future population, and income of the A1B scenario, no future climate change (see Table 2 for sector definitions).

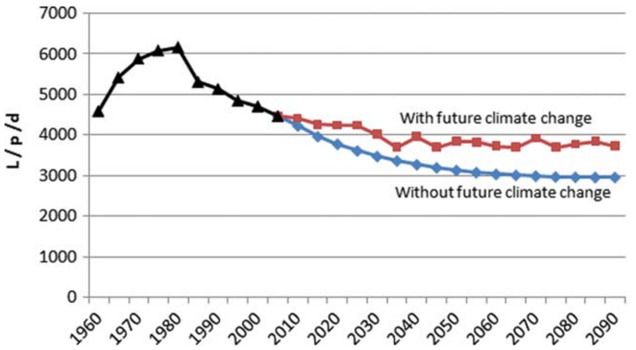

Figure 5. Past and projected U.S. daily withdrawal per capita for the A1B scenario with and without future climate change (with future climate change based on a multimodel average).

(Figure 5). Most of the decrease occurs in the early decades of the century; later decreases are smaller because of the assumed attenuation of the efficiency improvements (Table 4).

[68] The projected decrease in total withdrawal over the next 20 years or so is attributable largely to the TF and IR water use sectors (Figure 4). The largest decrease occurs in the TF sector, as a result of the continuing improvement in the efficiency of withdraws (Φ^{TF}) and the dramatic increase in electricity production at other renewable (e.g., wind and solar) plants, which use little or no water. The drop in withdrawals at thermoelectric plants is projected to bottom out in 2035 as the annual increase in production at other renewable plants diminishes to the point where it no longer compensates fully for the increasing demand for electricity; of course, technological advances could alter this situation. The drop in irrigation withdrawals, which is projected to continue through 2090, occurs because the effects of the improvement in withdrawal efficiency and the drop in irrigated area in the west more than compensate for the effect of the increase in irrigated area in the east.

[69] In contrast to the decreases in TF and IR withdrawals, total withdrawals in the DP and LA sectors are projected to rise continuously, and withdrawals in the IC sector are projected to remain nearly constant for about two decades and then rise. The increases in the DP and IC sectors occur because the projected improvements in withdrawal efficiencies are insufficient to compensate for the increases in population and income. Finally, LA withdrawals are projected to increase largely because of the rising population and an expanding aquaculture sector.

[70] As would be expected given the relative levels of population among the three scenarios (Figure 2), projected withdrawals of the A1B scenario fall in between those of the A2 and B2 scenarios (Figure 3). In comparison with the projected 3% increase in withdrawal by 2060 with the A1B scenario, projected withdrawal changes from 2005 to 2060 for the A2 and B2 scenarios are 8% and −9%, respectively; corresponding changes from 2005 to 2090 are 28% for A2 and −10% for B2, in comparison with +13% for A1B.

[71] Projected changes in water withdrawal vary widely across the ASRs. For example, from 2005 to 2060 with the A1B scenario the withdrawals are projected to drop in 42 of the 98 ASRs, increase by less than 25% in 38 ASRs, and increase by more than 25% in the remaining 18 ASRs (Figure 6). 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%. Reasons for the largest percent increases vary by location. For details on the importance of individual sectors by ASR, see *Foti et al.* [2012].

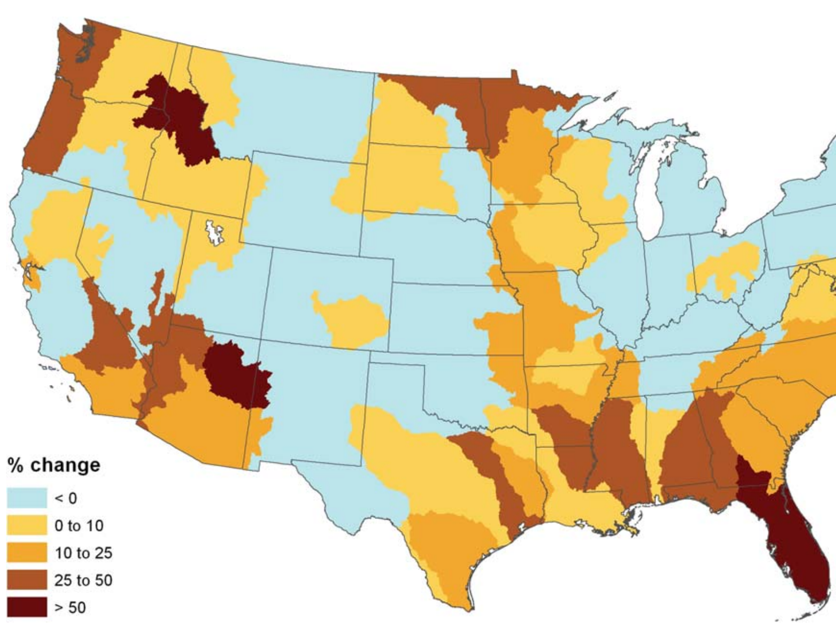

Figure 6. Change in ASR withdrawal from 2005 to 2060, given population and income of the A1B scenario, no future climate change.

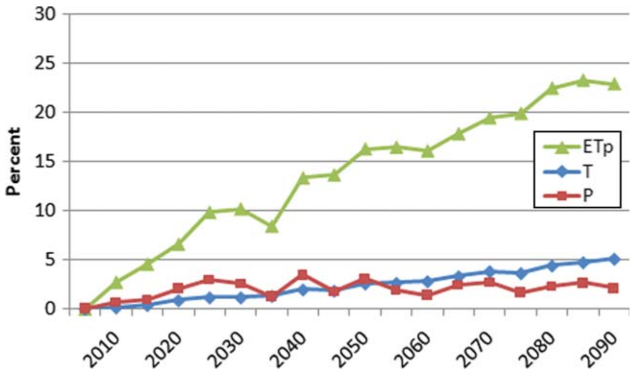

Figure 7. Trends in effects of climate change on projected total annual withdrawal in the U.S., averaged over the nine scenario-model combinations (percent change in withdrawal from a future with no climate change to a future with climate change caused by projected changes in potential evapotranspiration, temperature, and precipitation).

6.3. Climate Effects

[72] Climate change has the potential to radically alter the projections of the previous section. The projected changes in water use attributable to future climate change were computed by comparing projected water use in a given future year assuming no future climate change with projected water use for that year with climate change, in both cases allowing socioeconomic conditions to change as indicated for the corresponding scenario.

[73] Averaging across the nine scenario-model alternative futures, the effect of future precipitation changes is minimal, causing at most a 3.5% increase in the total U.S. withdrawal through 2090 above what is projected to occur without future climate change (Figure 7). The precipitation effect is due to the change in agricultural irrigation and landscape watering that occurs as precipitation varies above or below the 2001–2008 average. Although specific regions of the U.S. are projected to experience either increases or decreases in precipitation, at the national scale little change in precipitation is projected (Table 3), leading to little change in total withdrawal. The temperature effect is slightly larger than the precipitation effect, reaching 3% in 2060 and 5% in 2090. The temperature effect is due to increasing water use at thermoelectric plants to accommodate the electricity needed to satisfy increasing space cooling demands that occur with rising temperatures (Table 3). In contrast to the precipitation and temperature effects, the ETp effect is quite large, reaching 16% in 2055 and 23% in 2090. The ETp effect is due to the change in irrigation and landscape watering as plant water use responds to changes in atmospheric water demand. (The ETp effect might be lessened somewhat by the direct effect of rising atmospheric CO_2 levels on plant water use per unit area, a possibility that is undergoing much study [*Leakey et al*., 2009].) The combined (temperature, precipitation, ETp) effect of a changing climate is to increase total withdrawal in the U.S. by about 20% in 2060 and by about 30% in 2090, as compared to a future without climate change.

[74] Separating the effects of future climate change from the effects of changes in population and income, and focusing on the combined (temperature, precipitation, ETp) climate effect for the A1B scenario as an example, we see that changes in projected withdrawals from 2005 to 2060 attributable to climate change tend to be larger in the west than in most of the east (Figure 8). This difference occurs largely because the water use sectors most affected by climate change (DP and IR) account for little of total withdrawals in the east (for example, in 2005, DP and IR withdrawals across WRRs 1–9 were each about 10% of total withdrawal, whereas 65% of total withdrawal occurred in the TF sector). In contrast, in the west the DP

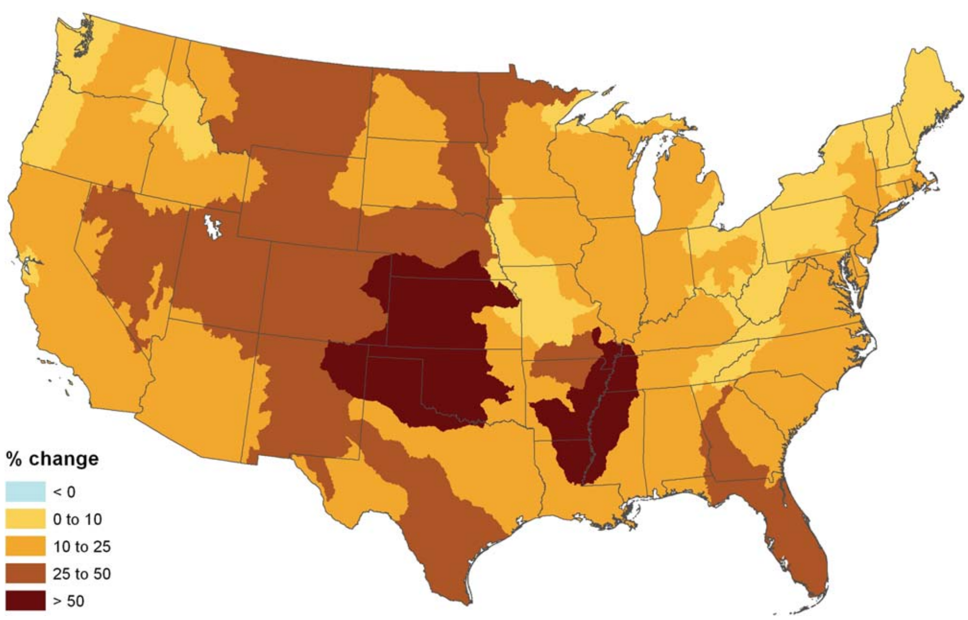

Figure 8. Change in ASR withdrawal from 2005 to 2060 attributable to climate change for the A1B scenario, multimodel average.

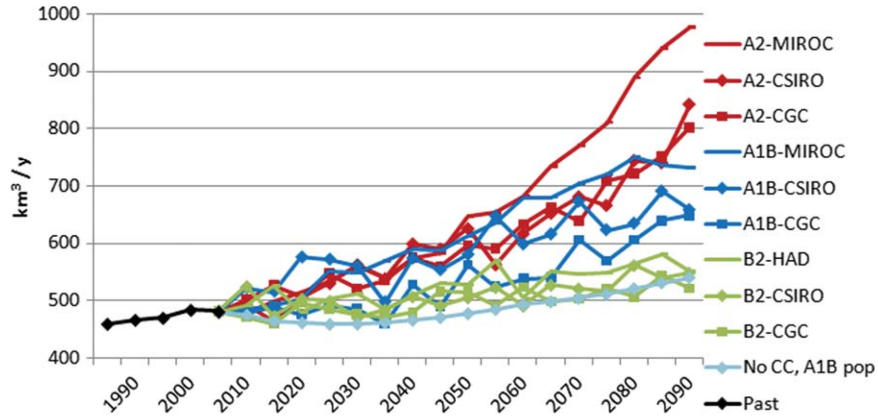

Figure 9. Past and projected withdrawal for the U.S. for alternative scenario-model combinations.

and IR water use sectors account for the majority of total withdrawals (in 2005, IR withdrawals across WRRs 10–18 were 68% of total withdrawal, with the DP sector contributing another 10%), causing withdrawals in the west to be much more sensitive to climate change than in the east. (Note that the multimodel average shown in Figure 8 masks the negative effect of climate change on withdrawals projected for a few ASRs with one of the three models, the CGC model.)

6.4. Projected Total Water Use Under a Changing Climate

[75] We now combine the socioeconomic effects with the climate change effects to project total future water withdrawals. For the U.S. as a whole, the projections vary greatly across the nine alternative futures (Figure 9). Projections for 2060 vary from 490 km^3 with the B2-CSIRO future to 681 km^3 with the A2-MIROC future. These projections for 2060 represent increases of 2% and 42%, respectively, above the 2005 withdrawal level of 480 km^3.

[76] In the early years of the projections there is much overlap among the withdrawal levels of the three scenarios, but by 2025 the projections of the B2 scenario are consistently below those of the A2 scenario and generally below those of the A1B scenario (Figure 9). By 2060, the projections for the A1B scenario are consistently below those of the A2 scenario for a given climate model. The A2 scenario combines the highest temperatures with the highest population, whereas the B2 scenario features the lowest levels of temperature and population. Averaging across the three climate models for each scenario, the U.S. withdrawals are projected to increase from 2005 to 2060 by 26%, 34%, and 5% for the A1B, A2, and B2 scenarios, respectively; corresponding increases from 2005 to 2090 are 42%, 82%, and 12%, respectively.

[77] The effects of future climate change are also seen in the projections of per capita withdrawal. Although, as mentioned above, daily per capita withdrawal for the A1B scenario drops to about 3000 L assuming no future climate change, it flattens out at about 3800 L with climate change (multimodel average, Figure 5). Of course, much depends on the scenario chosen. With future climate change, per capita withdrawal of the B2 scenario is similar to that of the no-climate change A1B scenario, but per capita withdrawal of the A2 scenario is projected to rise sharply after mid-century, reaching about 4000 L/d by 2060 and 4800 L/d by 2090.

[78] As without future climate change (Figure 6), with a changing future climate there is wide variation across the ASRs in projections of future water use (Figure 10). From 2005 to 2060 for the A1B scenario (multimodel average), withdrawals are projected to drop in 11 of the 98 ASRs, increase by less than 25% in 37 ASRs, increase by from 25% to 50% in 35 ASRs, and increase by more than 50% in the remaining 15 ASRs. All of the ASRs where withdrawals are projected to drop are in the east, but ASRs where withdrawals are projected to increase by more than 50% are scattered through the U.S.

[79] As mentioned earlier, the projected changes in temperature, and therefore ETp, are greatest in the latter half of the century. Based on a multimodel average, withdrawals for the A1B scenario over the period 2005–2090 are projected to decrease in only 4 ASRs, increase by from 25% to 50% in 31 ASRs, and increase by more than 50% in 40 ASRs.

6.5. Sensitivity Analysis

[80] Estimation of future withdrawal relied on a host of methodological decisions. Those decisions began with the selection of the scenario-GCM combinations to analyze and choice of downscaling method(s) to employ and continued on to the selection of methods used for estimating future changes in the water use drivers and for modeling future changes in the water use efficiency rates. Many sensitivity analyses could be performed to examine the effect of our methodological decisions. It is likely that some would indicate that the reported projections of withdrawal are conservative and that others would indicate the opposite. We include one analysis here, focusing on the method for estimating ETp, because of the importance of ETp in estimating the effect of climate change on future withdrawals.

[81] As reported in section 2, our projections of withdrawal utilized downscaled GCM data prepared by others for a multiresource assessment [*Joyce et al.*, 2013]. The downscaled data included only temperature and precipitation estimates, which limited options for computing ETp to a Linacre approximation of the Penman equation. To check on the effect of this data-based constraint, we subsequently went back to the original GCM-scale data for two GCMs,

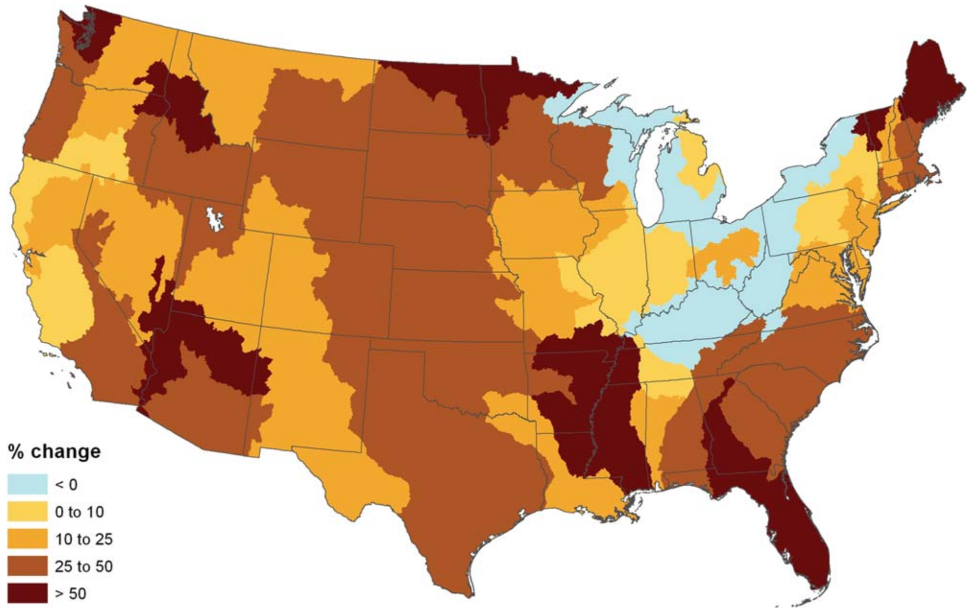

Figure 10. Change in ASR withdrawal from 2005 to 2060 for the A1B scenario, multimodel average.

CGC and MIROC, for the A1B scenario. These GCM-scale data contain additional variables useful in more fully implementing the *Penman* [1948] equation. Employing a simpler downscaling procedure than that used earlier (a bicubic interpolation scheme based on a nearest 4 × 4 neighborhood for each interpolated value), we produced fine-scale estimates of ETp and used those estimates along with the other inputs used before to recompute projected withdrawal.

[82] Using the Linacre approximation with these newly downscaled GCM data resulted in the estimates of ETp that closely matched those computed using the original downscaling. For the sensitivity analysis we compared the results of using the two ETp formulations each implemented with the newly downscaled data. In most ASRs, switching from the Linacre approximation to the Penman equation resulted in lower estimates of withdrawal. As expected, results differed by GCM. For the CGC model we found that, for 2060 as an example, using the Penman equation rather than the Linacre approximation resulted in a 2% reduction in the projected U.S. total withdrawal (518 km^3/yr versus 530 km^3/yr, respectively). Across the ASRs the median change was −1%; in six ASRs the reduction exceeded 10%. The largest reductions occurred in WRRs 13 and 14. However, for the MIROC model, again for 2060, using the Penman equation rather than the Linacre approximation resulted in a 13% reduction in the projected U.S. total withdrawal (604 km^3/yr versus 694 km^3/yr, respectively). Across the ASRs the median change was −5%; in 37 ASRs the reduction exceeded 10%. The largest reductions occurred in WRRs 10, 11, 13, and 14. These findings highlight the importance of ETp estimates in projecting future withdrawals.

7. Summary and Discussion

[83] This assessment has found that despite an expected 70% increase in population from 2005 to 2090 with the A1B scenario, in the absence of future changes in climate total water withdrawals in the U.S. would increase by only 13%, assuming water supply were no more limiting to growth in withdrawal than it has been in the recent past. This hopeful projection occurs largely because of the expected future gains in water use efficiency and reductions in irrigated area in the west. However, climate change has the potential to significantly alter water demands. With the A1B scenario, water withdrawals are projected to increase from 2005 to 2060 by from 12% to 41%, and from 2005 to 2090 by from 35% to 52%, depending on which climate model is used. Among the three models used with the A1B scenario, the MIROC model tends to yield the highest temperatures and lowest precipitation levels for 2090 and thus accounts for the upper end of the range. The CGC model accounts for the lower end of the range, but the CSIRO model yields a very similar result to that of the CGC model.

[84] The projected U.S. water withdrawals in the latter years of the century are much higher with the A2 scenario, and much less with the B2 scenario, than with the A1B scenario. With the A2 scenario, from 2005 to 2090 total withdrawals are projected to rise by from 67% to 103% depending on which climate model is used, compared with a 28% rise if the climate were not to change; and with the B2 scenario, withdrawals are projected to rise by from 9% to 15% across the three climate models compared with a drop of 9% without future climate change.

[85] These projections of water withdrawal, and the climate model outputs on which the projected effects of climate change rely, are educated guesses. The wide ranges for a given scenario highlight the uncertainty about the effects of increases in GHGs on temperature and precipitation, and the ranges across scenarios highlight uncertainty about future socioeconomic conditions. Further, as the sensitivity analysis showed, the selection of an ETp model can also affect results, especially for some climate projections and especially in some drier regions of the U.S. 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 scenario-model combinations and regardless of which ETp model is chosen the long-term large-scale effects of climate change are always to increase water demands (although in some of the nine combinations the effect of climate change is to decrease withdrawals in a few ASRs). In 2090, for example, the effect of future climate change, over and above the effect of changing socioeconomic conditions, on the projected U.S. withdrawals amounts to an additional 139, 258, and 107 km^3/yr with the A1B, A2, and B2 scenarios, respectively (in each case averaging across the three models used to simulate climate for the scenarios); 139 km^3 is 29% of the 2005 withdrawal level of 480 km^3.

[86] Among the three basic components of the effect of climate change on water use, the largest is that of increasing ETp on water used for agricultural irrigation and landscape watering, not that of increasing temperature on electricity demand or of changing precipitation. Increasing precipitation in some locations ameliorates the effect of ETp increases, but precipitation increases, where they occur, are insufficient to fully compensate for the ETp effect.

[87] Projected changes in withdrawal vary considerably by location. For example, for the A1B scenario simulated using the CGC model, total projected increases in the U.S. withdrawal from 2005 to 2090 with climate change are below 25% in 33 ASRs but over 50% in 29 other ASRs. The spatial variation reflects numerous differences in water use drivers (most importantly, differences in projected population, irrigated area, precipitation, and ETp) and in water use efficiencies.

[88] The projections presented here rely on many assumptions, none more important than that of irrigated area. Because irrigated area depends on so many factors that are themselves difficult to model, irrigated area was estimated by extrapolation from recent trends. Although this is a credible procedure in light of the difficulty of performing more involved modeling, unexpected changes in world markets or other factors could fundamentally alter the trajectory. Further, irrigated area may also change as a result of the increases in water withdrawals that are projected to occur in other sectors (irrigation in many areas being a lower-valued water use at the margin). This raises the question, how much would irrigated area need to decrease to compensate for the projected increase in total withdrawal? To take a specific situation, consider what change in irrigated area would keep total withdrawals in 2090 at a level no more than 10% above the 2005 level (thus, at about 528 km^3/yr rather than 649 km^3/yr as projected for the A1B-CGC future), holding all other withdrawal factors as projected. For the A1B-CGC future, analysis shows that this goal could be reached by reducing the total irrigated area by 59% compared with what it would otherwise be in 2090, clearly an unrealistic expectation.

[89] Calculating the effect on water withdrawal of reducing irrigated area is one of many sensitivity analyses that may be performed using the program developed to compute the projections presented here. In addition to seeing how a change in water use drivers would affect the projected withdrawals, we can also estimate the effect of changing water use efficiency rates. One interesting possibility is a change in the water withdrawal rate at thermoelectric plants, as such plants account for nearly 40% of total withdrawals. For the A1B-CGC scenario-model combination, to take a specific example, analysis shows that the goal of containing year 2090 withdrawals to 1.1 times the 2005 level could be reached by lowering both the eastern and western withdrawal rates at thermoelectric plants to 14 L/kWh (from the levels otherwise projected for 2090 of 53 and 25 L/kWh, respectively). Unlike a 59% reduction in irrigated area, such an improvement in the efficiency of water withdrawals at thermoelectric plants is probably attainable, although it would require retrofitting many plants, at significant cost. Note, however, that if reducing consumptive use, rather than withdrawal, were the objective (as indeed it might be to address future water shortages) attention would naturally focus on irrigation, which typically has a much higher consumptive use rate than do thermoelectric withdrawals. Additional sensitivity analyses, perhaps involving multiple water use sectors and combinations of changes in both water use drivers and efficiencies, and incorporation of consumptive use rates, are left for future work.

[90] The substantial increases in projected water use for most scenario-model combinations may not be sustainable, even if available water supplies do not diminish as the climate warms. Certainly the withdrawal increases imply alarming decreases in in-stream flow as well as substantial reallocations among water uses. If warming also tends to diminish water supplies, and this is indeed the expectation for many locations [e.g., *Barnett et al*., 2008; *Vicuna et al*., 2010], the water use levels projected for some areas of the U.S. will certainly not occur. Careful comparison of projected demand and supply [see *Foti et al*., 2012] is necessary to determine which ASRs are most vulnerable to future water shortages and therefore which would need to adjust water use and by how much.

[91] **Acknowledgments.** We thank Elizabeth Sink of Colorado State University for amassing the data on monthly municipal water deliveries; Susan Hutson of the USGS for counsel about USGS water use data procedures; Deborah Elcock of Argonne National Laboratory for helpful comments about power plant water use; and Joan Kenny of the USGS for a careful review.

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