

Earth's Future



RESEARCH ARTICLE

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Key Points:

- Dry regions see largest increases in freshwater use, with 8% decreases under best-case scenarios but 235% increases under worst-case scenarios
- Despite efficiency gains, population growth is expected to increase domestic water uses in fast growing regions
- Because agriculture is the dominant use of water in most regions, results vary more by climate model more than by socioeconomic scenario

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Projections of Freshwater Use in the United States Under Climate Change

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Abstract Water use in the United States reached its lowest level in 2015 in at least four decades. National trends, however, mask local challenges throughout the U.S. In some places, decreases in surface water use were more than offset by increases in groundwater use, leading to net increases in total withdrawals. Other places have seen increasing rates of water shortages caused by mixes of socioeconomic and climate forces. This study examines recent trends in freshwater use and makes projections in future freshwater use over the next 50 years. Projections are based on socioeconomic and climate scenarios from the Intergovernmental Panel on Climate Change Fifth Assessment Report. Scenarios are paired with five climate models from the downscaled Multivariate Adaptive Constructed Analogs (MACA). We find total consumptive water use will decrease by as much as 8% under the best-case scenario but increase by as much as 235% under the worst-case scenario. Results depend on both climate and socioeconomic changes, but because agriculture is the dominant use of water in most regions, climate change impacts overwhelm all other factors under hot and dry futures. For the wetter climate models, water use decreases even under the highest emissions levels and highest population growth rates.

Plain Language Summary This study examines recent trends in water use and makes projections for future water use over the next 50 years. Projections are based on scenarios consistent with international climate assessments and provided for a wide range of climate models. Water use could decrease by as much as 8% under the best-case scenario but increase by as much as 235% under the worst-case scenario. Because agriculture is the largest user of water in most regions, impacts of climate change on water use are larger than impacts from non-climate factors like population growth.

1. Introduction

Water use in the United States decreased 9% between 2010 and 2015, making 2015 the lowest level of water use since before 1970 (Dieter et al., 2018). Between 2005 and 2015, 64% of counties in the United States saw net decreases in surface water withdrawals (Figure 1). Decreases were especially widespread throughout the Great Plains. The decrease came despite population increases, in large part due to structural changes in the U.S. economy that favored less water-intensive industries and broad efficiency gains in household appliances, thermoelectric power generation, and agriculture irrigation.

National trends, however, mask challenges in many regions of the U.S. In some places (e.g., in Nevada and throughout the Mississippi River basin), decreases in surface water use were more than offset by increases in groundwater use, leading to net increases in total freshwater withdrawals. Other places have seen increasing rates of water shortages caused by mixes of socioeconomic and climate forces (Schewe et al., 2014; Warziniack & Brown, 2019). In 2018, over 1000 public water suppliers in Texas instituted water use restrictions in response to ongoing drought (Texas Commission on Environmental Quality, n.d.). A review by the Government Accountability Office found that 40 out of 50 state water managers expected water shortages to affect their state in the near term under what they describe as average conditions (U.S. Government Accountability Office (GAO), 2003).

This study examines recent trends in freshwater use and makes projections for future freshwater use over the next 50 years. Projections are based on socioeconomic and climate scenarios from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5; IPCC, 2014). The scenario approach uses plausible

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future pathways for carbon forcing (Representative Concentration Pathways, also known as RCPs) and socioeconomic conditions (Shared Socioeconomic Pathways, also known as SSPs; Moss et al., 2010; Nakicenovic et al., 2014; O'Neill et al., 2014). Scenarios are paired with five climate models from the downscaled Multivariate Adaptive Constructed Analogs (MACA), which together represent a range of socioeconomic and climate futures (Abatzoglou & Brown, 2012). Recently, the International Panel on Climate Change (IPCC) has released its Sixth Assessment Report, in which socioeconomic pathways were combined with RCPs in CMIP6. This study uses the CMIP5 convention where SSPs and RCPs are separate to examine the relative impacts of climate and socioeconomic forces and to be consistent with the approach used in the 2020 US Forest Service Resource Planning Act (RPA) Assessment, to which this study contributes.

Our projections are based on extrapolating past trends of withdrawal rates (e.g., water use per capita, irrigation depth) and applying those rates to projections of water-using units (population, acres irrigated). Similar approaches have been used in Brown et al. (2013), which this paper updates, and Duan et al. (2019), which focuses on the role of upstream and downstream hydrological connections on local water stress. Projections here differ in important ways from what the economics literature would typically refer to as water demand. Modeling water demand in the traditional economic sense would involve modeling demand functions and responses to price signals and other exogenous shocks. Estimating such functions for the entire U.S. would not only be difficult but would also imply a level of precision that is not realistic. We try to limit the assumptions and make the analysis as transparent as possible so we can identify factors that influence water outcomes. As such, water demands in our model are likely to be larger than models that maximize the value of water subject to total water availability (e.g., Dogan et al., 2018; Draper et al., 2003; Pulido-Velazquez et al., 2008) and models that estimate the water requirements needed to maintain current practices in a future with climate change (e.g., Blanc et al., 2014; Strzepek & Boehlert, 2010; T. Marston et al., 2020). Optimization models tend to reflect the best-case scenario and miss some of the forces already occurring in the economy that are likely to either magnify or alleviate some of the pains associated with climate change. Our approach highlights where the status quo is unsustainable and, therefore, where management actions are most needed.

The paper proceeds as follows: Section 2 describes socioeconomic scenarios and climate models that this analysis relies on. Projections of future freshwater use rely heavily on the literature and other data sources, and Section 2 lays the foundation on which this study's projections are based. Section 3 describes the methods used for sector-specific water use projections. It describes the general approach for all sectors, and a more detailed approach for water used in thermoelectric power generation. Section 4 presents projection results for each sector and total consumptive water use. Section 5 concludes.

2. Future Socioeconomic Scenarios and Climate Models

Projections focus on four core scenarios shown in Figure 2 and described in Langner et al. (2020). The core scenarios are a combination of SSPs 1, 2, 3, and 5 and RCPs 4.5 and 8.5. Economic and population growth are bound by the low-growth SSP3 pathway and high growth SSP5 pathway, with SSP1 and SSP2 representing moderate growth pathways. RCP 8.5 represents warmer global temperatures, and RCP 4.5 represents a less-warm future. In Figure 2, movements up and down show the relative impact of emissions levels, and movements left and right show impacts of the socioeconomic scenario. In reality, socioeconomic and emissions scenarios are tightly linked. To the degree possible, those differences and relative influences are described in this study.

County-level projections for population and income for SSPs are taken from Wear and Prestemon (2019) (Figure A1). Following historic trends, Wear and Prestemon project the southeast to have the highest rate of population growth, followed closely by the western U.S. In all scenarios, rural areas see little growth, or declining populations in the case of SSP3. Projections for personal income are jointly determined with population and follow similar patterns.

Climate futures are drawn from five MACA climate models for the Continental United States (CONUS) following Joyce and Coulson (2020). The models represent a range of temperatures and precipitation over the 21st century, including a wet, dry, hot, less warm, and middle climate model (Table 1). For the selected climate models, precipitation, potential evapotranspiration, and water yield are taken from Heidari et al. (2020). Heidari et al. (2020) use the VIC hydrological model - a macroscale semi-distributed hydrological model that simulates

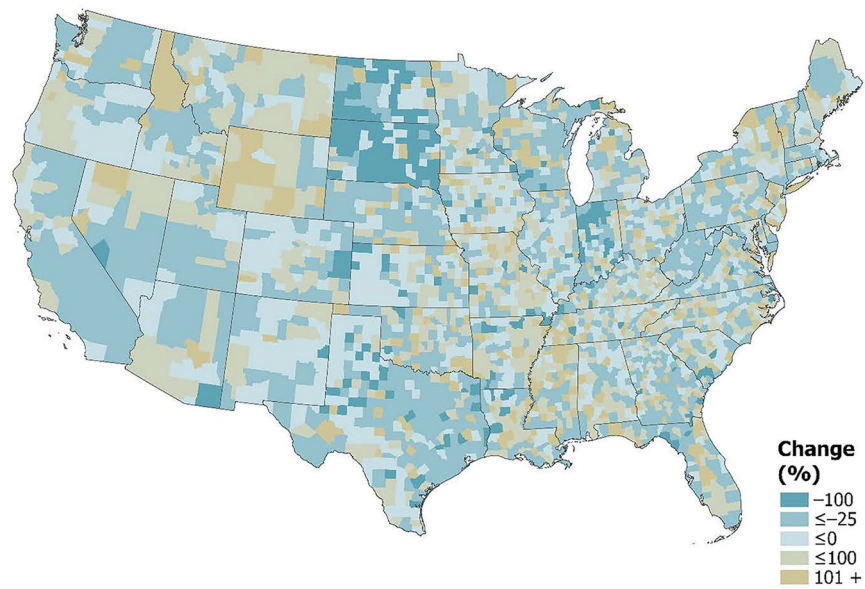


Figure 1. Percent change in surface freshwater withdrawals between 2005 and 2015 (data from Dieter et al., 2018).

land-atmosphere fluxes and water and energy balance at the land surface. VIC uses the Penman-Monteith equation to calculate potential evapotranspiration.

The climate projections show high variability between models. In the South, Southeast, and Great Plains, the dry climate model shows a decrease in water yield. The wet and hot models show increases in water yield for these same regions. The most consistent results across models are increases in precipitation and yield for much of the western United States and decreases in water yield in the South. Warmer temperatures in the South are projected to increase potential evapotranspiration (PET) more than for any other region of the U.S. Higher rates of PET amplify the effects of decreased precipitation in the South, leading to further declines in water yield. The majority

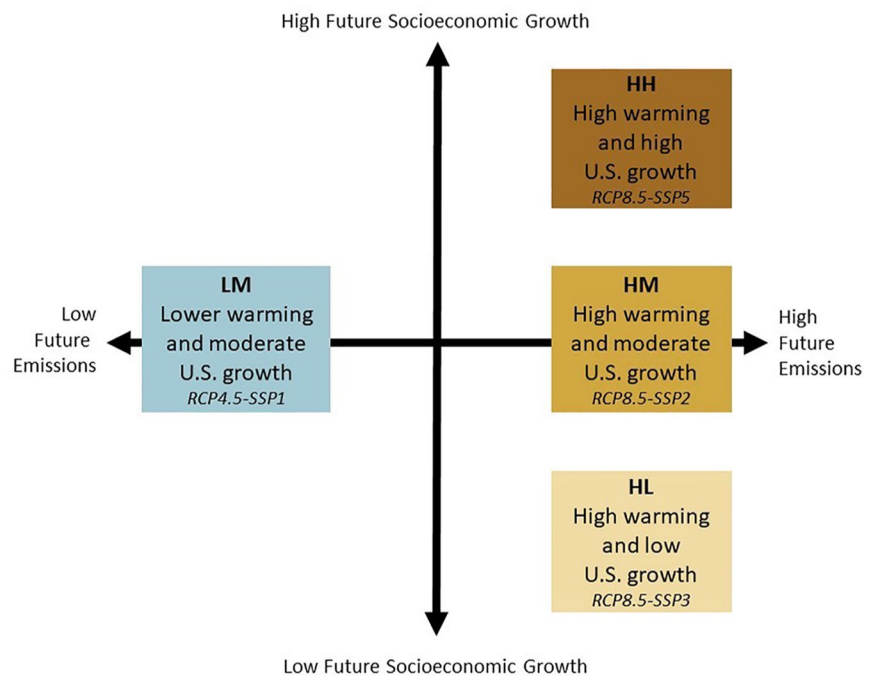


Figure 2. Core scenarios used in the water use projections (Langner et al., 2020).

Table 1
MACA Climate Models Used in Water Use Projections

	Hot	Warm	Wet	Dry	Middle
Name	HadGEM2-ES365	MRI-CGCM3	CNRM-CM5	IPSL-CM5A-MR	NorESM1-M
Model Agency	Met Office Hadley Center, UK	Meteorological Research Institute, Japan	National Center of Meteorological Research, France	Institute Pierre Simon Laplace, France	Norwegian Climate Center, Norway

Note. Details about model selection are given in Joyce and Coulson (2020).

of river basins in the western United States are projected to experience a decrease in PET, particularly under the wet and warm climate models.

3. Methods for Projecting Water Use

3.1. General Methods

The model builds on Brown et al. (2013), to which this work improves the spatial resolution of projections from water assessment subregions (ASRs) to counties and makes substantial changes to the way water use is modeled in the energy sector. It looks at withdrawals from freshwater sources, including from surface and groundwater sources, and calculates consumptive use for each sector. Sector-specific withdrawals represent the sum of publicly supplied water (water delivered by a municipality or water company) and self-supplied water (water withdrawn directly by the user) based on USGS water use sectors and baseline data.

Let $j \in J$ index the set of water use sectors. Withdrawals (W) in sector j , county y , at time t are computed as the product of water demand units (U) and an estimate of withdrawal per demand unit, also called a withdrawal rate (Φ) (Table 2):

$$W_{j,y,t} = U_{j,y,t} \cdot \Phi_{j,y,t} \quad (1)$$

A unit of demand, also called a water use driver, could be a person for domestic use or an irrigated acre for agricultural use, with the corresponding withdrawal rates measured in gallons per person and gallons per acre, respectively.

Withdrawal rates (Φ) are computed as the sum of the rate without the effects of climate change (Φ^{wo}) and, where applicable, the change in that rate caused by climate change ($\Delta\Phi^{cc}$):

$$\Phi_{j,y,t} = \Phi_{j,y,t}^{wo} + \Delta\Phi_{j,y,t}^{cc} \quad (2)$$

The effects of future climate change are estimated based on projections of annual or seasonal temperature, potential evapotranspiration, and precipitation obtained from downscaled global climate model runs (Heidari et al., 2020). Estimates of Φ^{wo} in future years are developed by extrapolating past trends based on data from US Geological Survey (USGS) circulars, particularly data after 1985 that consistently report withdrawals at the county level (Dieter et al., 2018; Hutson et al., 2004; Maupin et al., 2014; Solley et al., 1988, 1993). Past trends in rates of water withdrawal are estimated assuming that climate change has not affected past withdrawals (i.e.,

Table 2
Water Use Sectors, Drivers, and Withdrawal Rates for Water Demand

Sector (J)	Driver (U)	Withdrawal rate (Φ)
Domestic (DOM)	Population	gallons/person
Industrial and mining (IND)	Personal income	gallons/dollar of income
Thermoelectric power (THERM)	Population, total electricity use	Gallons/thermoelectric kWh produced using freshwater
Irrigated agriculture (IR)	Acres irrigated	gallons/acre
Livestock (LS)	Population	gallons/person
Aquaculture (AQ)	Population	gallons/person

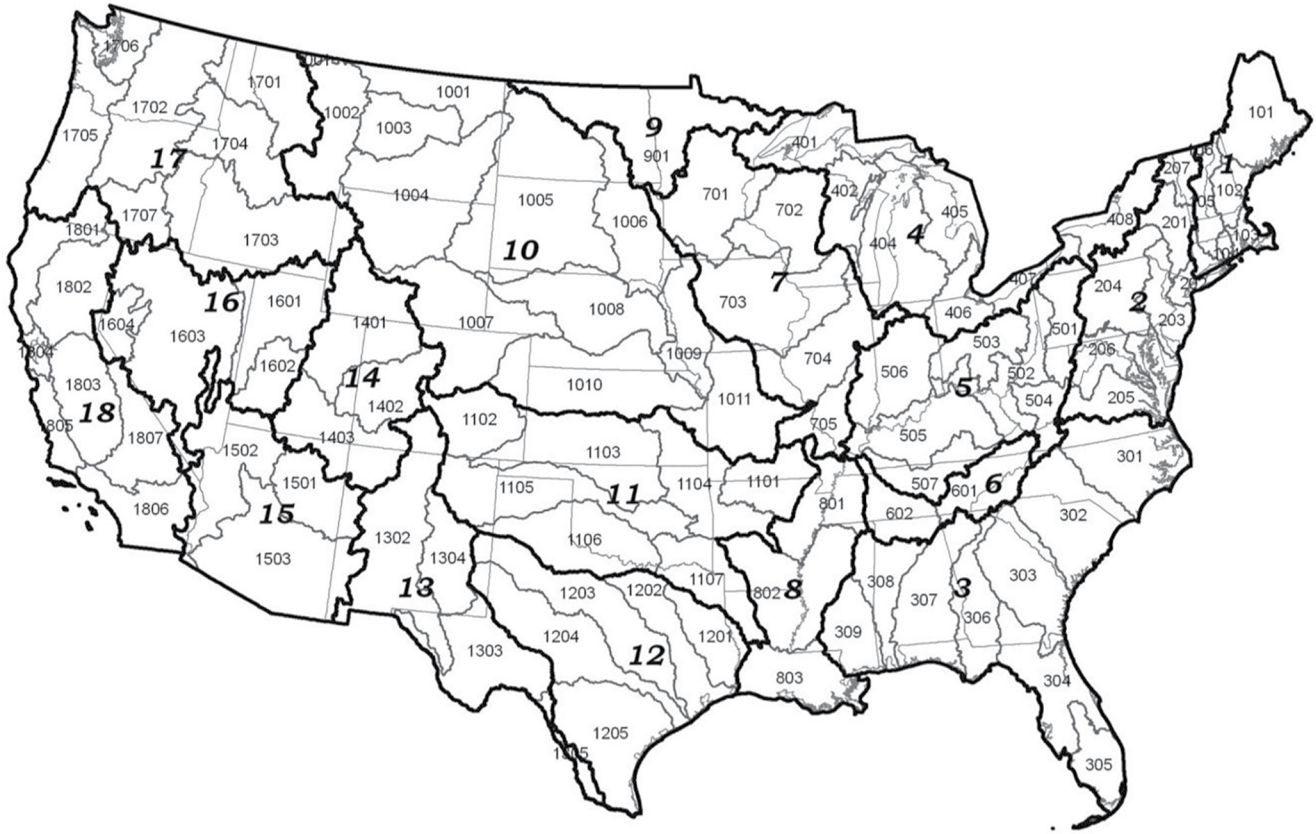


Figure 3. Water resource regions (WRRs) and assessment subregions (ASRs).

$\Delta\Phi^{CC} = 0$ in past years) and are based on periodic estimates of withdrawal divided by an estimate of the number of units of a water use driver:

$$\Phi_{j,y,t0}^{wo} = \frac{W_{j,y,t0}}{U_{j,y,t0}} \quad (3)$$

where $t0$ is the baseline data year.

Past trends in the rates of water withdrawal in most cases have been nonlinear, with the rate of change gradually diminishing. Extrapolation of past trends in Φ^{wo} is accomplished by applying an annual growth rate (g), based on data from recent years, along with corresponding decay in that growth rate (d). The decay rate was chosen to attenuate the trend, leading gradually toward a hypothesized equilibrium level (Brown et al., 2013). Given a 5-year time step for projecting withdrawals reflecting the USGS water use reporting schedule, the extrapolation procedure for a given future year t is as follows:

$$\Phi_t^{wo} = \Phi_{t-5}^{wo} [1 + g_{DIV}(1 + d_{DIV})^{t-t_0}]^5 \quad (4)$$

where DIV is a major division of the U.S., either the eastern division or the western division. The annual growth factor (g) and decay rate (d) are selected for most water use sectors to extend trends computed from all or part of the withdrawal record from 1985 to 2015. Divisions used to calculate growth and decay rates are specified according to Water Resource Regions (WRR) (2-digit hydrological units); the eastern division consists of WRRs 1–9 and the western division consists of WRRs 10–18 (Figure 3). Projected future water withdrawal is calculated at the county level, but the factors used to produce those estimates are specified at larger spatial scales because the data for individual counties are sometimes erratic—perhaps because of annual weather fluctuations or errors in estimation—so that they do not appear to support estimation at the smaller spatial scale (Brown et al., 2013). Likewise, estimates for baseline $\Phi_{j,y,t0}^{wo}$ are simple averages of the most recent three estimates to lessen the impact

of an individual estimate, as individual estimates may reflect the year's particular weather as well as unique methodological choices or errors. Most sectors use an average of the three most recent estimates (currently the estimates for years 2005, 2010, and 2015). Projection of thermoelectric power is an exception to the rule. Because we rely on a new data source for thermoelectric power, the year 2020 estimate of per-capita electricity use is based solely on an extension from the 2015 estimate.

Two facts complicate the projection of livestock and aquaculture withdrawals using these methods. First, these categories consist of water use by several different animal species and kinds of aquaculture operations, and site-specific data on numbers of animals or areas and kinds of fish farms are not easily obtained. Without accounting for numbers of livestock animal units by species (on the range and then in feedlots and other confined areas) and the area of fish farm, there is no obvious summary unit of production. Second, livestock products are often not consumed where they are produced, so future changes in county livestock withdrawals will not be proportional to changes in county population.

For projecting future water withdrawals, the first fact (lack of data on-demand units) is accommodated by basing future withdrawals not on numbers of animals or area of fishponds but rather on the human population, as humans are the consumers of livestock products. The second fact (spatial mismatch between production and consumption) is accommodated by computing total livestock and aquaculture withdrawals at the WRR spatial scale and then apportioning that total to individual counties based on the location of past withdrawals. Thus, the driver for livestock is the WRR population, and the withdrawal rate is gallons per person. This method for projecting livestock demands ties water use to domestic demand for livestock products, that is, meat consumption. 11 percent of US domestic beef production was exported in 2020 (USDA, 2021). Given the small share of total water withdrawals from the livestock sector, errors associated with relying on domestic markets are likely to be small. Furthermore, exports of livestock are driven more by trade policies and shocks such as the reduction in trade tariffs by Japan and removal of trade barriers in China than global food demand. Predicting trade policies and modeling their impacts are beyond the scope of this study.

Withdrawals in each sector are converted to consumptive use $C_{j,y,t}$ using withdrawals in each sector according to proportions at the state level, $\gamma_{j,state}$:

$$C_{j,y,t} = W_{j,y,t} \cdot \gamma_{j,state} \quad (5)$$

Consumptive use is the amount of water withdrawn that is not returned to the system as runoff or wastewater; it represents the amount of water that is unavailable for other uses. For most water use sectors, consumptive use proportions are adapted from USGS estimates for 1985, 1990, and 1995 (the last three years for which the USGS estimated water consumption); the exception is the thermoelectric sector, as described below. Total water consumption in a county y is estimated for future year t as the sum of water consumption across water use sectors:

$$C_{y,t} = \sum_{j \in J} C_{j,y,t} \quad (6)$$

While baseline withdrawals in the model are from freshwater sources, the model is mute on how future withdrawals will be satisfied. Increases in consumptive use are assumed to be met without regard to the availability of water supply – they are projections of *desired* water use. One possibility is that withdrawals are taken from sources (fresh, saline, surface, ground) in the same proportion as in the base data, such as in Duan et al. (2019). Because water supply is not a constraint to actual withdrawals, such an assumption is not necessary at this point but would be needed in vulnerability analysis.

3.2. Climate Effects on Domestic and Agricultural Withdrawals

The change in withdrawals per capita in the domestic sector attributable to climate change, $\Delta\Phi_{cc}^{DOM}$, is computed as a combination of the effects of changes in precipitation and potential evapotranspiration:

$$\Delta\Phi_{cc}^{DOM,y,t} = \Delta P'_{y,t} \cdot \eta^P + \Delta ETp_{y,t} \cdot \eta^{ETp} \quad (7)$$

where:

1. $\Delta P'$ is change in effective precipitation, the portion of total growing season precipitation that is useable by the plant, from $t0$ to the future year, in cm/y, computed at the county scale
2. η^P is the change in DOM gallons per capita per day withdrawn for a 1 cm increase in P' from $t0$ to a future year, a constant equal to -1.415
3. ΔETp is the change in potential evapotranspiration during the growing season, from $t0$ to the future year, in cm/y, computed at the basin scale; and
4. η^{ETp} is the change in DOM gallons per capita per day withdrawn for a 1 cm increase in ETp from $t0$ to a future year, a constant equal to 0.778

η^P and η^{ETp} are estimated for the U.S. as a whole based on regressions using data at the WRR scale. See Brown et al. (2013) and Foti et al. (2012) for further details.

As with domestic withdrawals, the change in irrigation withdrawals per acre attributable to climate change, $\Delta\Phi_{IR}^{CC}$, is computed as a combination of the effects of change in precipitation and change in potential evapotranspiration. However, unlike with domestic water use, here the effect of climate change translates directly into a change in water use under the assumption that irrigation completely satisfies the plant water requirement (i.e., that water will not be a limiting factor in plant growth):

$$\Delta\Phi_{IR,y,t}^{VV} = \vartheta \frac{-\Delta P'_{y,t} + \Delta ETp_{y,t}}{\gamma_{WRR,1990-95}^{IR}} \quad (8)$$

where:

1. ϑ is 0.0328, the number of feet per centimeter
2. $\Delta P'$ is change in effective precipitation (the portion of total growing season precipitation that is useable by the plant) from $t0$ to the future year, in cm/y, computed at the basin scale
3. ΔETp is the change potential evapotranspiration during the growing season, from $t0$ to the future year, in cm/y, computed at the basin scale, and
4. dividing by the consumptive use proportion converts the result to feet of withdrawal

3.3. Thermoelectric Freshwater Use

Projecting freshwater use at thermoelectric plants is complicated by the fact that electric energy consumed in one basin may be produced in another, and because electric energy is produced at not only freshwater thermoelectric plants but also at saltwater thermoelectric, hydroelectric, solar, wind, and other types of plants. Recently released USGS estimates of thermoelectric water use in 2010 and 2015 (Diehl & Harris, 2014) allow for a new approach to projecting water use at thermoelectric plants that solves much of this issue. The earlier approach to estimating water use in the thermoelectric sector relied on the quinquennial USGS water use circulars, wherein the USGS used the EIA estimates of thermoelectric water withdrawal, which, it was generally acknowledged, were not as accurate as of the EIA's estimates of fuel consumption or electricity generation at thermoelectric plants (Harris & Diehl, 2017).

The new USGS approach utilizes EIA-reported data on fuel consumption and net electricity generation, in light of water availability, to model the heat and water budgets of 1,274 individual thermoelectric utility plants (those with a generating capacity of at least 1 MW) across the contiguous U.S. Separate functions are used for different electricity generation types and cooling system types. Of the 1,274 plants, 1,213 are listed as withdrawing water, and of those 112 use saline water, leaving 1,101 for use herein. The 1,213 plants can therefore be assigned to basins based on individual plant locations. The new approach solves another problem as well by providing estimates of water consumption, as opposed to just estimates of water withdrawal, making it unnecessary to rely on the consumptive use proportions computed from the USGS water use circulars for 1990 and 1995. Comparison of the Diehl and Harris (2014) estimates of water use at freshwater thermoelectric plants in 2010 with those produced using the earlier approach, which relies on Maupin et al. (2014) for 2010 withdrawal by county and estimates of consumptive use proportions from the 1990s (see Brown et al., 2013), reveals that the two approaches produce quite similar estimates of withdrawal and consumption for the U.S. as a whole but very different estimates for some individual WRRs. As would be expected, estimates at the smaller basin-scale show some even greater percentage differences than those indicated for WRRs.

To project water consumption for thermoelectric generation for each future year at the county level, net electric energy produced at freshwater thermoelectric plants is projected in each county as is the rate of water consumption (water consumed per unit of electricity produced) at freshwater thermoelectric plants in the county. This is done by first projecting future growth in per-capita electricity demand by state using EIA data in 2015 on thermoelectric generation and consumption by state and sector, assuming the share of thermoelectric plants is relatively constant into the future. This is a simplifying assumption. Historically, the shares of electricity generation by source in the United States have stayed constant. However, in 2020 we already see a significant shift in the electricity generation mix. In 2010 coal was over 45% of the US electricity generation, but today it is 28%, with most of the difference being made up by natural gas, but some by renewables. The EIA projects that by 2050 renewables would be as large as 31%, with natural gas accounting for 39% of domestic electricity production, and coal will only be 12% (U.S. Energy Information Administration, 2019a). Nuclear power generation is also expected to slowly fall from its current 19%–12%. Decreases in nuclear power and shifts towards gas steam and renewable energy are likely to cause large decreases in water withdrawals and consumption. This suggests that projections here will provide a baseline for future water use keeping with the status quo but will likely over-project future water use for thermoelectric generation.

The growth in per-capita demand is expected to grow according to past trends but at a decaying rate due to gains in energy efficiency and declines in manufacturing. The reasons for past declines, especially the movement from once-through to recycling plants, are likely to continue to play a role, suggesting recent past trends are a good indication of future changes. It is assumed here that the rate from 1985 to 2015 will carry on into the future, but be gradually attenuated, to keep with recent declines in the growth rate (Brown et al., 2013). Estimates of industrial and commercial electricity demand per unit of income and residential electricity demand per person are combined with population and income projections from Wear and Prestemon (2019) to get county-level electricity demand.

To account for electricity demand in one county that might be met by electricity generated in another, demand is aggregated up to the eight energy regions defined by the North American Reliability Corporation. After the demand is projected at the energy region level, demand is apportioned to each county based on the county's relative population. Finally, water consumption rates are applied to the projected electricity demand for freshwater thermoelectric generation to get projected water consumption for thermoelectric generation by county.

3.4. Climate Effects on Thermoelectric Withdrawals

The change in thermoelectric water use needed to accommodate the increase in space-cooling with a rise in temperature is computed by introducing a multiplier M to represent the effect of the temperature increase on the per-capita electricity consumption (E^p). The change in C_{THERM} from a change in temperature is then total thermoelectric production with the temperature increase minus total production absent the temperature increase:

$$\Delta C_{THERM} = C_{THERM} \cdot (M - 1) = \rho \cdot E^p (M - 1) \Phi_{THERM}$$

where ρ is population, E^p is electricity consumption per capita in kWh and Φ_{THERM} is the amount of water withdrawn and consumptively used for thermoelectric generation in gallons per kWh.

Impacts of temperature changes have both short-term and long-term effects on electricity use (D. J. Sailor & Pavlova, 2003). In the short term, for example, residents and businesses decide daily whether to use their air conditioners. In the long term, people without air conditioners decide whether to purchase air conditioners. Factors for the short-term effect (M^{ST}) and the combined effects (M^{ST+LT}) are estimated at the WRR level because the limited data available on the effects of temperature on electricity did not justify producing estimates at a smaller scale.

Short-term effects are based on Sailor (2001), who estimates the percentage increase in residential and commercial electricity consumption for annual temperature increases for eight states. Combining residential and commercial uses, Sailor's estimates are applied to other states using data on past (1971–2000) temperatures and state-specific nonlinear regression equations expressing the percent change in E^p as a function of change in temperature. These state-level relations were matched to WRRs based on the proportion of a WRR in that state. The equations for short-term effects are of the form:

$$M^{ST} = (\Delta T \cdot x_1 + \Delta T^2 \cdot x_2)/100$$

Table 3
Coefficients for Computing the Change in Thermoelectric Energy Production With Climate Change

WRR	Residential		Commercial		x3
	x1	x2	x1	x2	
1	0.14	0.02	0.59	0.04	2.63
2	0.63	0.11	0.90	0.06	1.62
3	3.05	0.45	1.71	0.12	1.06
4	0.26	0.07	0.72	0.06	1.90
5	0.76	0.16	1.04	0.08	1.67
6	1.62	0.28	1.28	0.09	1.36
7	0.54	0.10	0.71	0.05	1.90
8	2.29	0.40	1.49	0.11	1.06
9	0.09	0.01	0.35	0.03	2.12
10	0.27	0.05	0.68	0.05	1.36
11	1.49	0.23	1.14	0.08	1.36
12	2.36	0.22	1.01	0.07	1.06
13	1.63	0.19	1.03	0.08	1.06
14	0.09	0.01	0.73	0.05	1.67
15	2.10	0.36	1.43	0.10	1.06
16	0.19	0.03	0.83	0.06	1.47
17	1.12	0.08	0.29	0.09	2.33
18	1.59	0.23	2.16	0.12	1.63

M^{ST} is the proportional increase in electricity consumption due to short-term effects and ΔT is the change in annual temperature in degrees Celsius. The coefficients x_1 and x_2 for the short-term impact by WRR are listed in Table 3.

Sailor and Pavlova (2003) estimated short-term and long-term residential electricity consumption changes for 12 cities located in four different states: California, New York, Ohio, and Texas. This information was used to estimate the ratio of the total percent increase to a short-term percent increase. The ratios for the 12 cities were extended to the 18 WRRs in the contiguous United States by selecting cities or groups of cities that were considered most representative of the WRRs. The resulting ratios (x_3) are listed in Table 3. As seen in the table, the long-term effect is smallest in southern, hotter areas (e.g., WRRs 3, 13, 14, and 15) and rises progressively moving north, except WRR 17, which includes the state of Washington and is a special case.

The combined short-term plus long-term proportional increase in electricity consumption with an increase in temperature is:

$$M^{ST+LT} = x_3 M^{ST}$$

In 2015, the residential and commercial sectors consumed 37 and 36% of U.S. electricity production, with these shares staying relatively stable through 2018 (U.S. Energy Information Administration, 2019b, Table 2.2). Applying these proportions across WRRs, the multiplier (M) for change in C_{THERM} due to a temperature change is:

$$M = 1 + 0.36 M^{ST} + 0.37 M^{ST+LT}$$

4. Results

As shown in Figure 4, the amount of water used and the purpose for which it is used varies throughout the United States. In the West, supplemental irrigation is needed to meet the needs of crops and is the largest user of water in the West. In the East, agriculture uses less water than it does in the West because precipitation largely meets the needs of eastern agriculture; thermoelectric power generation, however, uses considerably more water than it does in the West. Results are presented for each sector as mean percent change in consumptive use across scenarios (climate models, RCPs, and SSPs) and standard deviation in percent change.

4.1. Domestic Water Withdrawals

In 2015, domestic water use made up 9% of national withdrawals. Between 2005 and 2015, domestic water use decreased by 10%, even though U.S. population increased by 7% (US Census Bureau, National Intercensal Tables), continuing a downward trend going back to the 1990s in national domestic withdrawals per capita. The national withdrawal rate for domestic use was 120 gallons per capita per day (GPCD) in 1990 and was 98 GPCD in 2005. By 2015, that figure had dropped to 82 GPCD. Reductions in water use rates can be attributed to reductions in outdoor water use, newer buildings, and more efficient appliances, including low-flow toilets, high efficiency showerheads and faucets, and government policies (Gleick et al., 2009; Lee et al., 2013; Millock & Nauges, 2010). U.S. population, the principal driver of domestic water use, is projected to increase by 24%–44% by 2070 under moderate growth scenarios and by 56% under the high growth SSP5 scenario (Wear & Prestemon, 2019). Furthermore, the highest rates of population growth are expected in the driest parts of the country, with the population doubling in the West and Southwest under the high growth SSP5 scenario. Despite these increases, for low and moderate growth scenarios, most regions of the U.S. are expected to see declines or only modest increases in domestic water use (Figure 5). The exception is the southern and western parts of the U.S. In these regions, population growth is expected to outpace improvements in water use efficiency, leading to increases in domestic water use across all scenarios. Under the high growth SSP5 scenario, all but 10 counties across the U.S. are projected to see increases in domestic water use, compared to the low growth SSP3 scenario

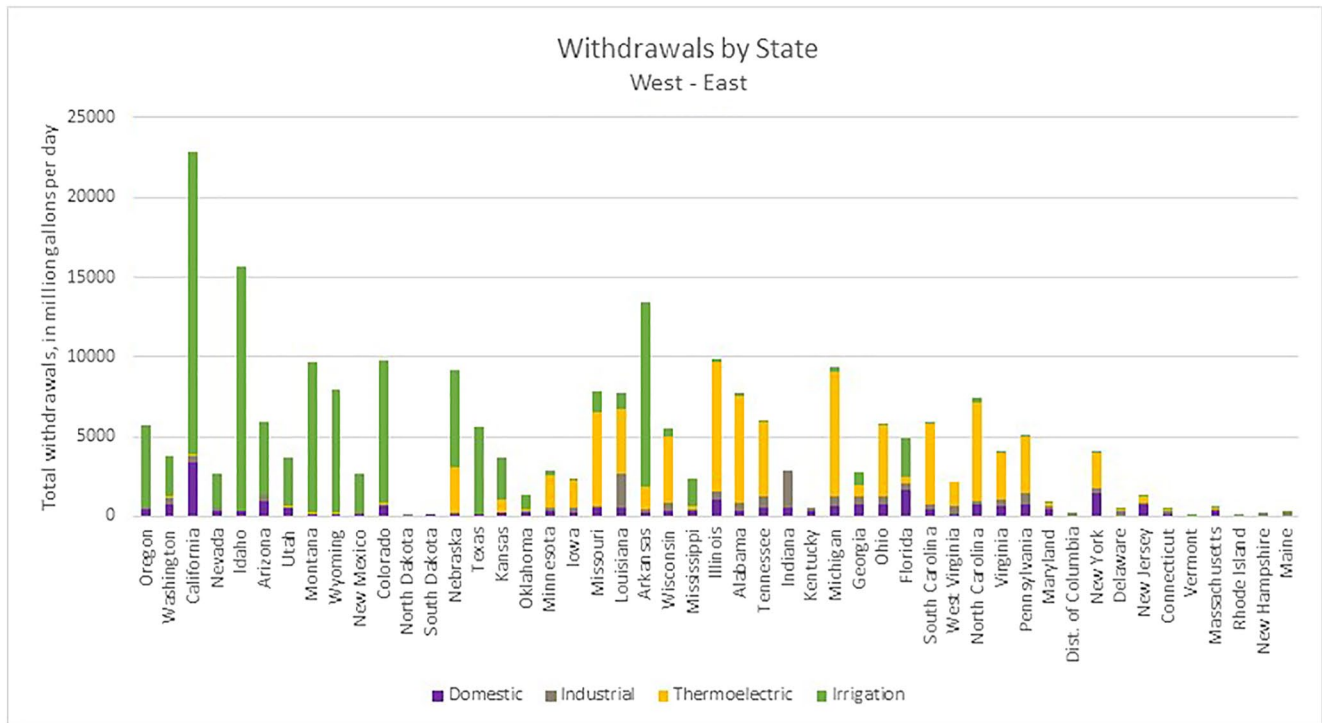


Figure 4. 2015 water withdrawals for each sector by state. States are ordered from West – East, left – right, based on Dieter et al. (2018).

for which 78% of counties are projected to see decreases in domestic water use. Climate change compounds the effects of population, leading to more water use as households offset decreases in precipitation with increases in water withdrawals for outdoor use. So while population drives most of the use, the high levels of uncertainty tend to be where climate models differ (Figure 6b).

4.2. Industrial and Commercial Use

Industrial water withdrawals have been declining at an annualized rate of 1.8% since at least 1985. They are highest in urban areas, regions with large manufacturing industries (like the Great Lakes region), and regions with heavy concentrations of paper production and petroleum refining (like the Southeast and Gulf regions). Declines in industrial water use are due to improvements in water efficiency within factories and structural changes throughout the U.S. economy (Dieter et al., 2018; Wang & Hejazi, 2011). Growth in the service and information industries, which use relatively little water, has outpaced manufacturing growth over the last couple of decades.

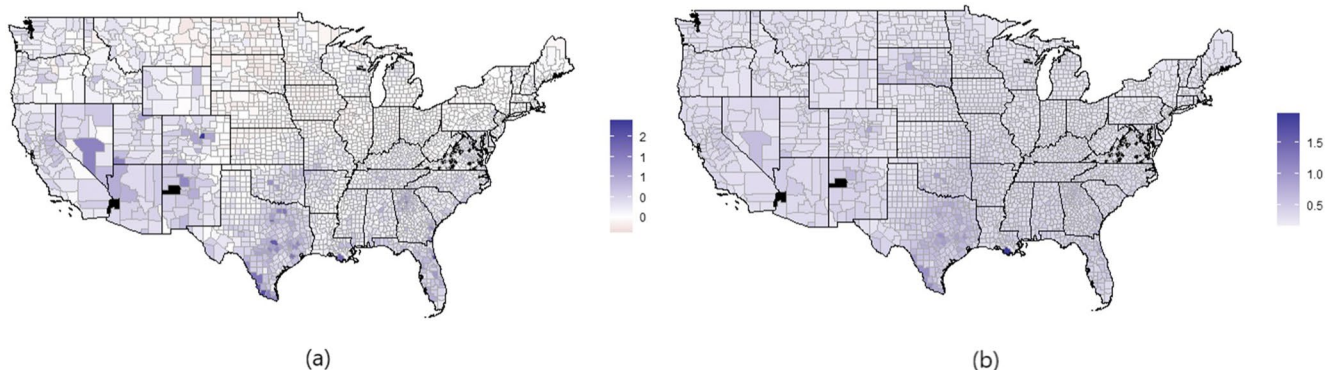


Figure 5. (a) Mean percent change in domestic water consumption across scenarios. (b) Standard deviation in percent change in domestic water consumption across scenarios.

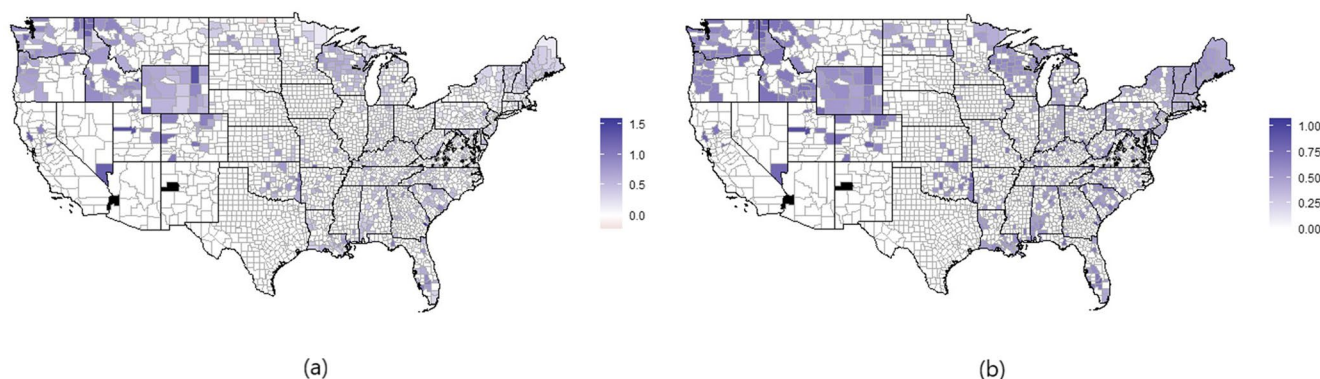


Figure 6. (a) Mean percent change in industrial water consumption across scenarios. (b) Standard deviation in percent change in industrial water consumption across scenarios.

Between 2005 and 2015, real GDP in manufacturing was essentially stagnant while the economy as a whole grew by 14%, and the information sector grew by 42% (U.S. Bureau of Economic Analysis, “Industry Economic Account Data”). These trends are expected to continue, leading to only modest increases in industrial water use for moderate growth scenarios and declines in industrial water use for the low growth scenario (Figure 6). Under the high growth scenario, however, both the northern and southern Great Plains see large increases in industrial water use. This is significant because those regions also see decreased precipitation (appendix Figure A2) and an increased likelihood of shortage in some climate scenarios. On average, the Pacific Northwest, Northeast, Great Lakes, and pockets of the South see increases in industrial water use. Wyoming also sees growth, but the baseline is so low that small increases represent large percentage changes. Because industrial growth is driven by per capita income, the map of standard deviations mimics that for percent changes.

4.3. Thermoelectric Use

In 2015, thermoelectric generation was the second-largest user of freshwater, accounting for about 34% of all freshwater withdrawals. In the east, thermoelectric power generation is by far the dominant user of water (Figure 5), both because eastern agricultural needs are largely met by precipitation and abundant water supply has led to slower adoption of more efficient cooling technologies among eastern power plants. Nationally, about 3% of thermoelectric withdrawals are consumptively used though rates vary considerably by region and choice of technology. Power plants are transitioning to closed loop cooling systems, in which water is circulating several times in the plant for cooling. Under such systems, withdrawals are lower, but the percentage of water consumptively used can be quite high. In comparison, once-through (open loop) systems withdraw water from a local water body such as a lake, river, or ocean and subsequently discharge back to the same water body. As a result, plants equipped with once-through cooling water systems have relatively high-water withdrawal, but low water consumption.

Figure 7 shows percent change projected in water used for thermoelectric generation throughout the U.S. between 2015 and 2070. Per-capita demand for electricity has been falling at an average rate of 1% since 2000 due to gains in energy efficiency (U.S. Energy Information Administration (EIA) State Energy Data System). However, the EIA estimates that gross domestic product growth will drive a small but positive increase in per-capita electricity demand. Thermoelectric consumptive water use is projected to see annual increases out to 2070, and per-capita electricity demand for thermoelectric power is projected to increase by at least 150% for moderate growth scenarios and by over 400% for extreme cases. Thermoelectric water consumption is projected to rise from just under 2.5 billion gallons of water per day in 2015 to between 5 and 17 billion gallons per day, depending on the combination of socioeconomic and climatic outcomes.

In 2015 the East accounted for roughly 74% of thermoelectric consumptive water use; by 2070, that share is expected to fall to 71% due to broader use of efficient cooling technologies in the East and faster growth in electricity demand in the West. The South Atlantic-Gulf region is expected to dominate the share of thermoelectric water consumption in the United States, followed by regions in the Midwest and Texas-Gulf. Regions west of Upper

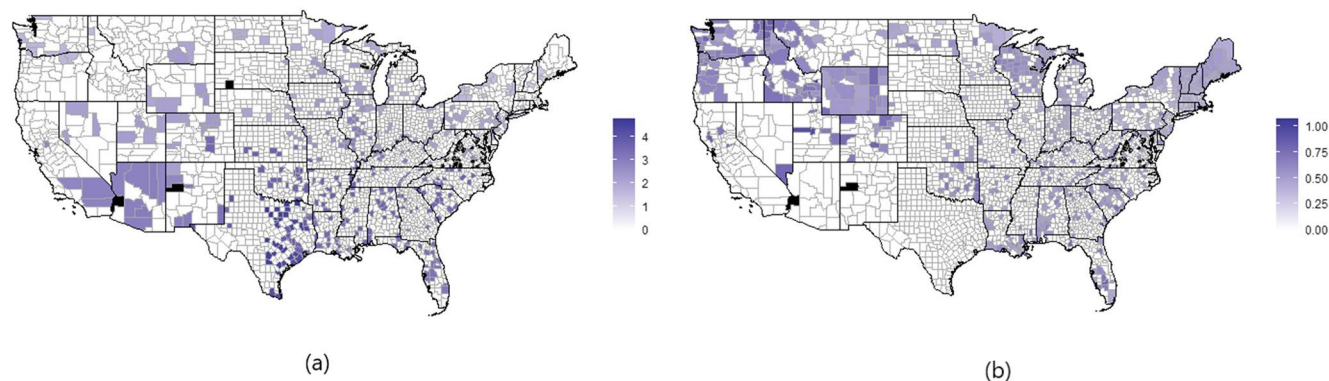


Figure 7. (a) Mean percent change in consumptive use water for thermoelectric power generation across scenarios. (b) Standard deviation in percent change in consumptive use water for thermoelectric power generation across scenarios.

Colorado tend to use the least amount of water for thermoelectric generation and, in some regions, will continue consuming less than 100 million gallons per day. In contrast, the South Atlantic Gulf is estimated to consume nearly 800 million gallons per day in 2070 in the lowest projections.

Warmer temperatures associated with climate change could increase water use for power generation by 20%–60%, depending on the scenario. More drastic weather changes will cause greater variation in year-to-year consumption levels over time. Rising temperatures could increase thermoelectric water use by an extra 6 billion gallons per day in extreme cases beyond what would occur based on population growth alone.

4.4. Irrigation

Irrigated agriculture accounts for 42% of total freshwater withdrawals, making it the largest user of freshwater in the U.S. Historically, agricultural water demand in the east has been smaller in both areal extent per basin and irrigation depth than in the West. Over the last couple of decades, however, eastern farmers have increased their irrigation use to provide larger and more reliable yields. In most locations, water supplies in the eastern U.S. are ample and increases in irrigation are not expected to affect other uses. A few exceptions occur for areas in the Southeast, such as Florida, that are seeing both rapid population growth and expansion of irrigated agriculture (Florida Department of Agricultural and Consumer Services, 2016). In the West, growing population and more frequent drought has increased competition between agricultural water users and municipalities, leading to both improvements in irrigation efficiency and reductions in total water use for agriculture.

Between 1985 and 2010, the national average irrigation depth on an acre of farmland hovered around 2.5 feet per year; in 2015, that rate was down to nearly 2 feet. In the West, irrigation rates are higher (2.3 feet in 2015) but have been falling consistently at an annualized rate of 0.85% between 1985 and 2015. Acres irrigated in the West are projected to decline from about 46,800 acres in 2015 to just under 46,000 by 2070. However, declines in precipitation due to climate change will need to be offset by increases in irrigation rates. All told, this implies there may be a net increase in water used for agriculture in parts of the West (Figure 8). Because western river basins are mostly appropriated, increases are shown in Figure 9 for the West essentially showing areas where adaptation will be most needed. Both withdrawal rates and acres irrigated are projected to increase in the East, and total water used for irrigation in the United States is projected to increase from 116 billion gallons in 2015 to 134 billion gallons in 2070. The higher standard deviations in California, for example, are due to large differences in water yield between models. The wet and warm climate models show California getting wetter by mid-century under RCP 8.5.

4.5. Livestock and Aquaculture

Livestock accounts for less than 1% of total withdrawals in the US; aquaculture accounts for 2% of total withdrawals. Thus, the sector has little impact on total withdrawals nationally but may affect withdrawals in some areas with large operations. Texas, California, Iowa, Nebraska, and Kansas together made 42% of total livestock

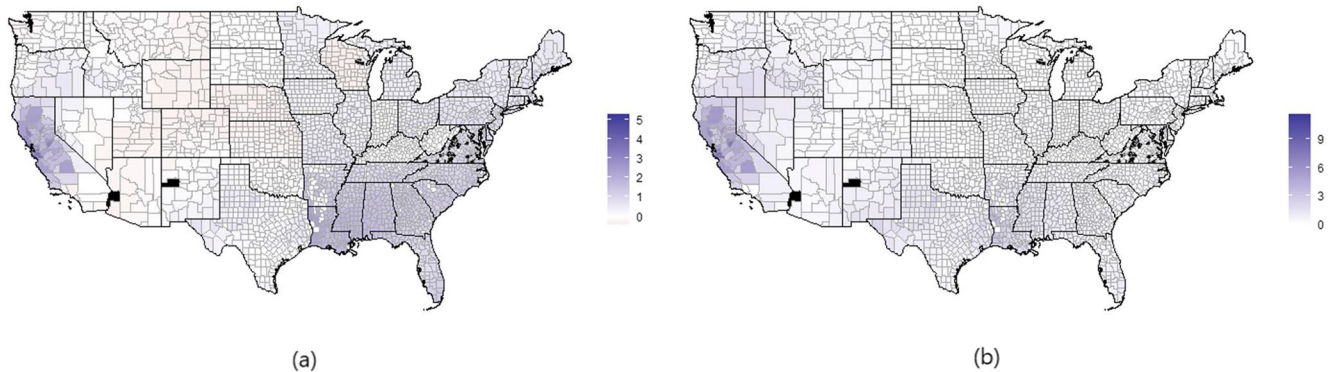


Figure 8. (a) Mean percent change in consumptive use water for irrigated agriculture across scenarios. (b) Standard deviation in percent change in consumptive use water for irrigated agriculture across scenarios.

withdrawals in 2015. 57% of total aquaculture withdrawals were in Idaho, North Carolina, California, and Oregon. Our projections of livestock water demand do not include climate effects, so only vary by SSP (Figure 9). The West and parts of the Southeast see relatively large increases in water use for many of the scenarios. Increases are significant in the intermountain region, which has the largest amount of use among regions. The increase in the Intermountain west under all but the low growth scenario is larger than the total withdrawals in all other regions. This increase is a product of the amount of livestock raised in the region as well as the population growth projected in the region.

4.6. Projections of Total Consumptive Use

In many sectors, water is withdrawn returns to the stream either as wastewater effluent or runoff. The portion that is not returned, and thus not available for downstream use, is called consumptive water use. The portion of withdrawals consumptively used vary by sector and region. In agriculture, for example, differences in crops and growing practices lead to a consumptive use rate of 77% in California and a consumptive use rate of 28% in Wyoming (Dieter et al., 2018).

Nationally, total consumptive use is projected to decrease by as much as 8% in the RCP 4.5 - SSP1 scenario and increase by 235% in the RCP 8.5 - SSP 5 scenario (Figure 10). Because agriculture is the dominant use of water in most regions, results often vary by climate model more than they do by SSP, particularly under RCP 8.5. In the Intermountain region, where irrigated agriculture makes up roughly 90% of consumptive use, RCP 8.5 projections lead to total consumptive use nearly twice as high in the dry scenario as in the wet scenario. Under RCP 4.5, climate impacts are small and total consumptive use falls far from many regions.

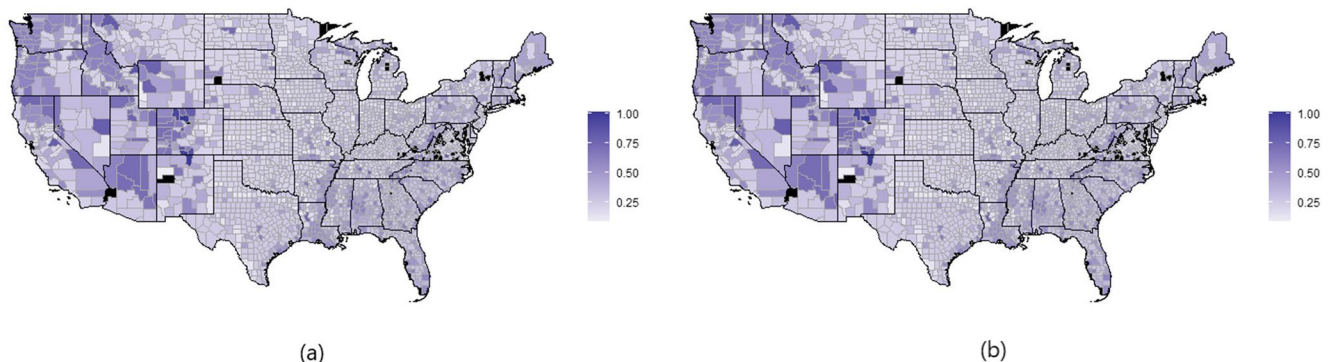


Figure 9. (a) Mean percent change in consumptive use water for livestock and aquaculture across scenarios. (b) Standard deviation in percent change in consumptive use water for livestock and aquaculture across scenarios.

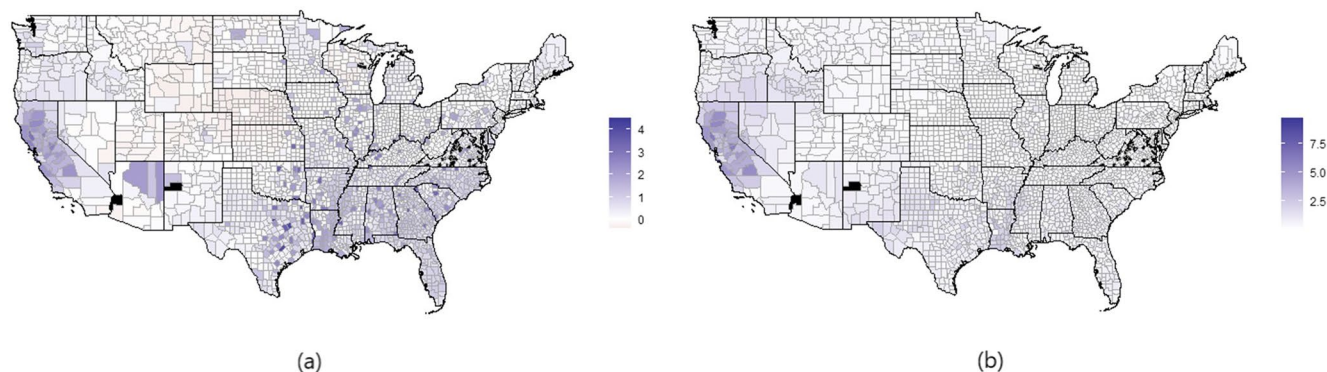


Figure 10. (a) Mean percent change in total consumptive use across scenarios. (b) Standard deviation in percent change in total consumptive use across scenarios.

5. Conclusion

Climate models show a wide range of futures for the United States. Under dry climate models, the South, Southeast, and Great Plains show decreases in water yield. Those same regions, however, see increases in water yield under wet scenarios. Models are relatively consistent in showing increases in water yield for much of the western United States and decreases in water yield for the South. For the drier areas, farmers and households will have to increase their water use to maintain crops and lawns. The hot and dry models see large increases in water use in agriculture, particularly in the Pacific Southwest and South-Central U.S. under RCP 8.5. The wet and middle climate models lead to sizable decreases in irrigation water demand in the Intermountain West, where agriculture accounts for 90% of total withdrawals. Because agricultural accounts for the largest share of withdrawals, these changes in agricultural water demand overwhelm most other impacts due to climate.

Socioeconomic factors are the primary determinants of water use in the domestic sector. Despite significant gains in water use efficiency among households, population growth is expected to outpace efficiency gains in many parts of the United States, including in some of the driest regions of the country. Under the high growth SSP5 scenario, populations in the West and Southwest double, leading to increases in domestic withdrawals. In the South-Central US, domestic water use is projected to double under the dry model with SSP5 and RCP 8.5.

This interaction between socioeconomic and climate impacts is also seen in the thermoelectric sector, which response to the increased electricity demands of a larger population and the increased demand per person due to warmer temperatures. These projections assume technology and the share of thermoelectric generation will remain near current levels. The rapid shift toward less carbon-intensive energy technologies and the electrification of the transport sector complicates future impacts on electricity demand at thermoelectric plants and subsequent water use rates, particularly at regional levels (Clemmer et al., 2013; Macknick et al., 2012; Peer & Sanders, 2018; Strzepek et al., 2012). Future increases in energy-efficient technology are expected to outpace growth in income at the national level. The Energy Information Administration estimates that for a 1.9% annual increase in gross domestic product, energy consumption will rise 0.3% annually (US. Energy Information Administration (EIA), 2020). Projections here serve as a benchmark for potential water demand for a thermoelectric generation if the status quo continues.

Aggregate impacts of climate and socioeconomic changes depend on which future the U.S. sees. For the wet and middle climate models, water use decreases even under with the highest emissions levels and highest population growth rates. Under the best-case scenario, water use decreases by 8%, but under the worst-case scenario water use increases by 235%. National averages, however, mask regional challenges. Results for the driest parts of the country suggest a future with both less water and higher demand, leading to even more frequent shortages than currently seen.

The good news is that water users have made considerable improvements in efficiency in recent decades, with withdrawals in 2015 the lowest they have been since before 1970. Necessity breeds invention, especially in the water sector. While these results capture recent efficiency gains, future innovation could be more rapid. Indeed, in many places, it will have to be, as these results assume water supply is not a limiting factor in water use. Constrained by water availability, significant adaptation measures will be needed (Warziniack & Brown, 2019).

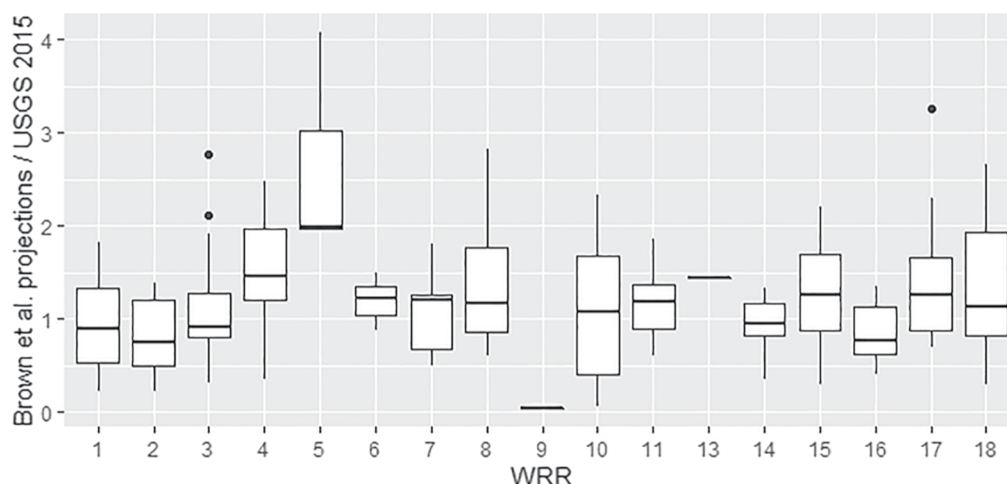


Figure 11. Ratio of 2015 withdrawal projections from Brown et al. (2013) to 2015 withdrawal data from USGS circulars. WRRs 9 and 13 have several missing data points that prevent meaningful comparisons.

There is a large amount of uncertainty in these projections - future drivers of water use (e.g., climate, population) are uncertain; the way Americans use water is rapidly changing, and because of these projections do not include notions of scarcity. While the methods differ slightly from those in Brown et al. (2013), they are similar enough to shed light on model performance. At the time projections were made in Brown et al. (2013), the most recent USGS data was from 2010, to 2015 was the first year of projections. Since then, the USGS has released 2015 water use data allowing a comparison of their projections with the reported data. Across all watersheds in the United States, their A1B scenario projected about 20% more water withdrawn in 2015 than was reported by the USGS. Figure 11 shows the ratio projections to USGS circular data by water resource region (WRR). For the most part, their projections did fairly well. The largest overestimates were for WRRs 4 and 5 (the Great Lakes and Ohio regions); the largest underestimates were for WRRs 2 and 16 (Mid-Atlantic and Great Basin regions). These differences between projections and observed data represent economic shifts larger than those observed in historical data trends. Large declines in manufacturing led to reductions beyond what was expected in manufacturing centers of the U.S. In some places with heavy agricultural water use, droughts were met with increases in water use to protect crops while in other areas drought spurred larger reductions than projected.

Appendix

A1. Population and Income Projections

Population and income projections are taken from Wear and Prestemon (2019). They downscale national projections of population and income to the county-scale. Their approach is based on principles in the economic growth theory of jointly determined population and income and uses fixed-effects panel models to quantify the spatiotemporal process of labor migration. Figure A1 shows their results at the national level for each SSP.

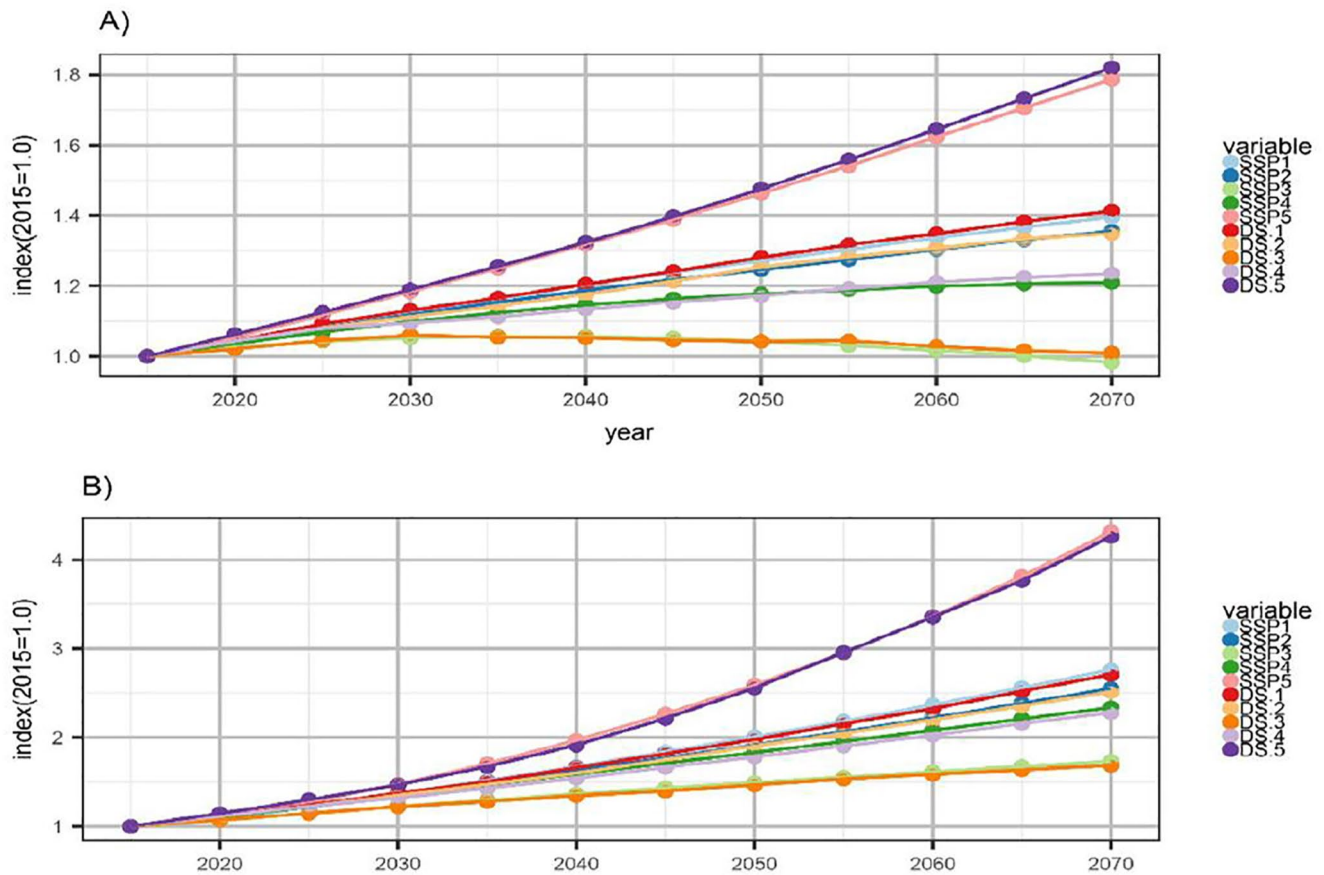


Figure A1. Population and Gross Domestic Production (GDP) projections from Wear and Prestemon (2019). Projections of indices of (a) US Population, and (b) GDP (in constant 2005 dollars) projected for five socioeconomic pathways (SSPs) indexed to a value of 1 in 2015. SSPx is the U.S. projection for the reference SSP and DS.x is the sum of the downscaled county-level projections for the reference SSP.

A2. Climate and Water Yield Projections

Figures A2, A3 and A4 show changes in the spatial patterns of precipitation, water yield, and potential evapotranspiration under the five selected MACA models and two RCPs for mid-century (2041–2070) and end-of-century (2070–2099) from Heidari et al. (2020). Projections are based on results from the Variable Infiltration Capacity (VIC) hydrological model at the 4×4 km spatial resolution.

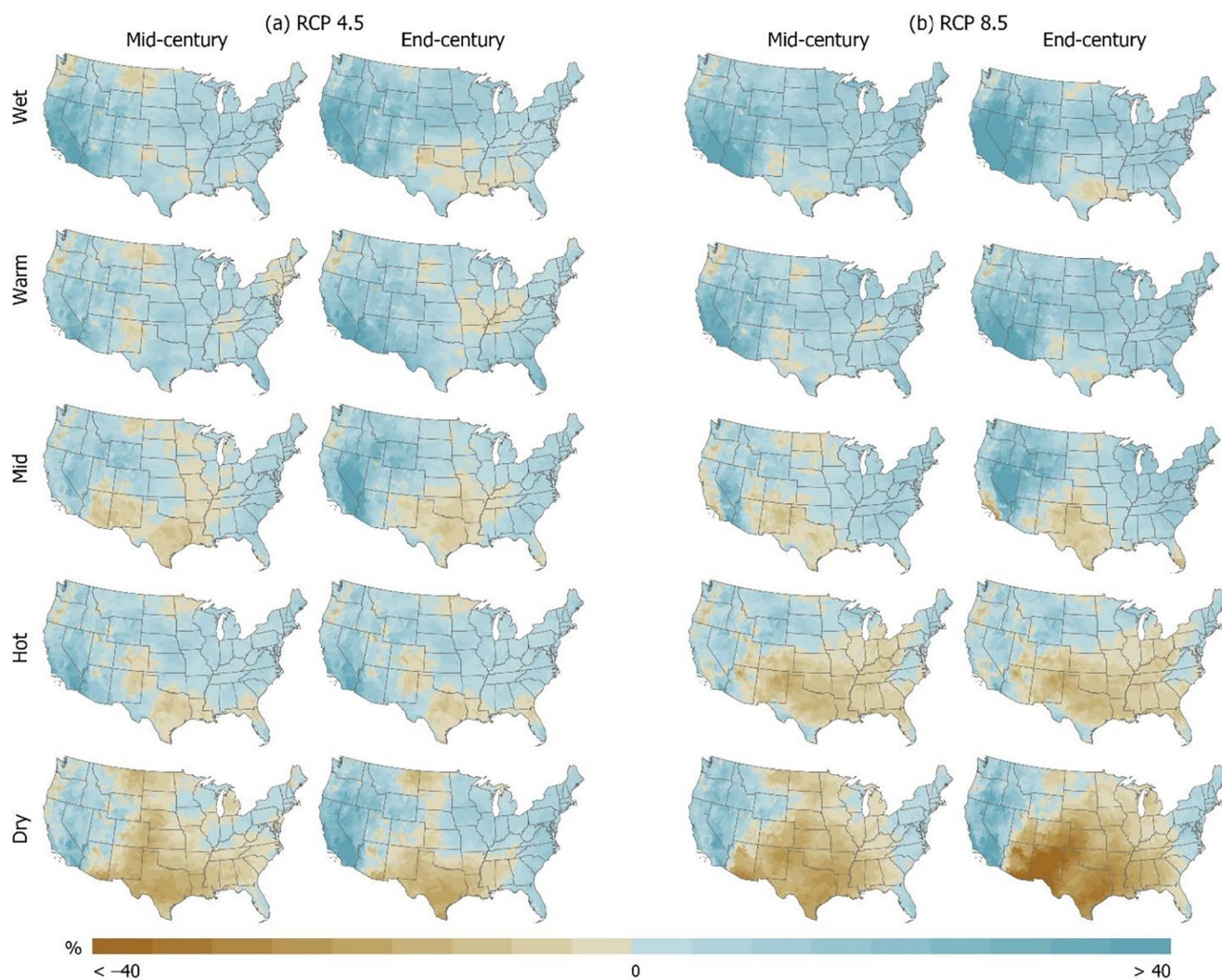


Figure A2. Spatial changes in 30-year average of annual precipitation in response to future climate change: (a) RCP 4.5; and (b) RCP 8.5.

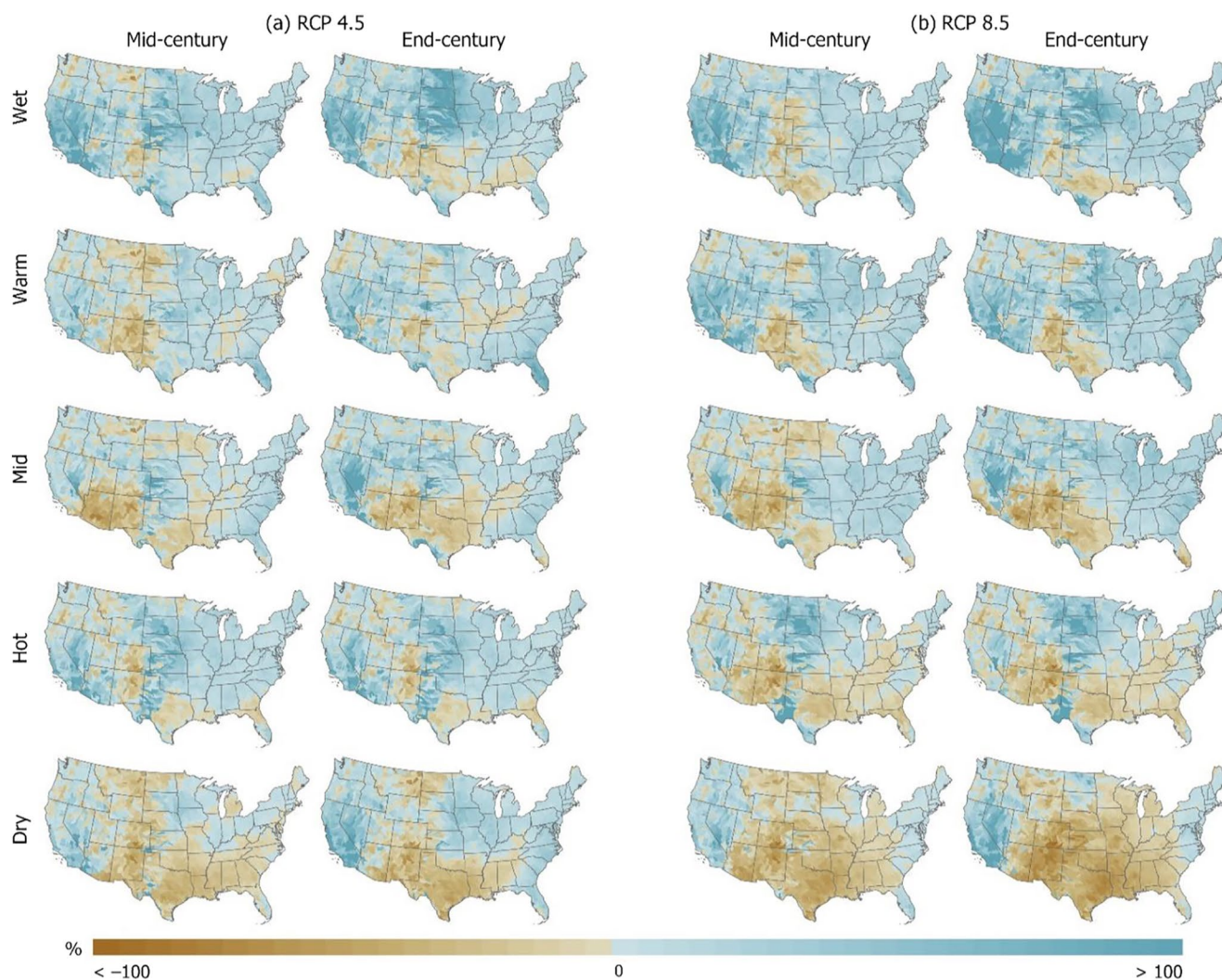


Figure A3. Spatial changes in 30-year average of annual water yield in response to future climate change: (a) RCP 4.5; and (b) RCP 8.5.

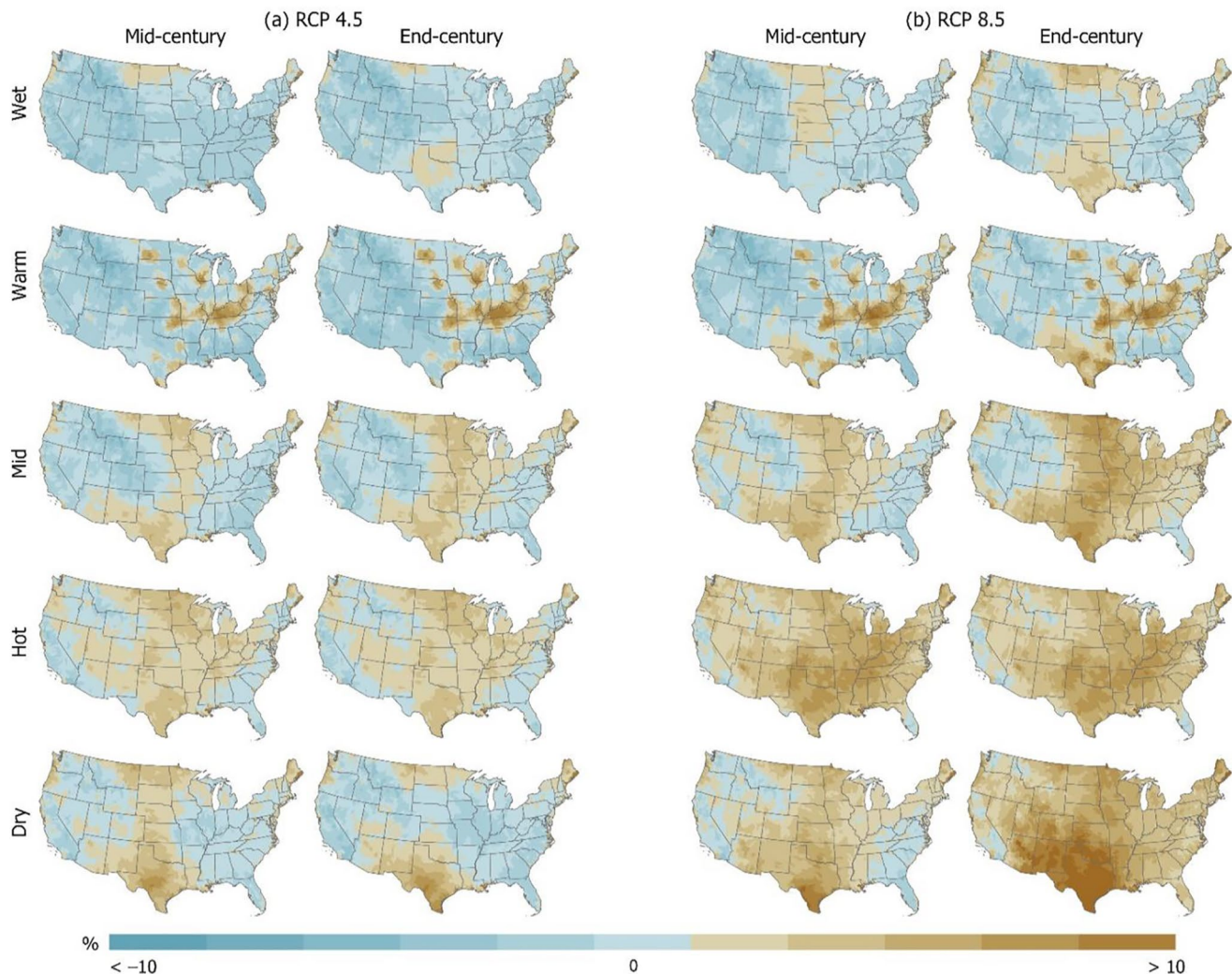


Figure A4. Spatial changes in 30-year average of annual potential evapotranspiration in response to future climate change: (a) RCP 4.5; and (b) RCP 8.5.

Data Availability Statement

Following peer review of this manuscript, the data used here will be archived in the US Forest Service Research Data Archive <https://www.fs.usda.gov/rds/archive/>.

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