Chapter 9
Water Resources

Warziniack, Travis; Arabi, Mazdak; Froemke, Pamela; Ghosh, Rohini; Heidari, Hadi; Rasmussen, Shaundra; Swartzentruber, Ryan. 2023. Water Resources. In: U.S. Department of Agriculture, Forest Service. 2023. Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment. Gen. Tech. Rep. WO-102. Washington, DC: 9-1–9-20. Chapter 9. https://doi.org/10.2737/WO-GTR-102-Chap9.

In this chapter, we examine trends in freshwater use and supply throughout the conterminous United States and their implications for future shortages due to socioeconomic and climate change. We focus on renewable freshwater, which includes surface and subsurface flows, and provide projections of freshwater supply and likelihood of water shortage under future scenarios. Regarding the sources of water supply, we found that 39 percent of all water within the conterminous United States originates on forested lands. Percentages are higher in the Eastern United States, where forests make up a larger share of the land base. Relative shares of water from forests are lower in the Western United States, but the percentage that comes from national forests is much higher, highlighting the need to manage public and private forests for sustainable water resources.

Among the most encouraging trends in water resources is the tremendous gains in water use efficiency. Water use in the United States decreased 9 percent between 2010 and 2015, making 2015 the lowest level of water use since before 1970 (Dieter et al. 2018). This decrease came despite population increases, in part due to efficiency gains in household appliances, thermoelectric power generation, and irrigated agriculture, along with structural changes within the U.S. economy that have favored less water-intensive service industries over traditional manufacturing (Dieter et al. 2018, Wang and Hejazi 2011). Both per capita water use and total water use have declined throughout the country. From households to agriculture to industry, meaningful changes have occurred in human behavior and conservation practices. Nonetheless, large regions of the United States

Key Findings

- Both per capita water use and total water use are declining in many parts of the country.
- Despite reductions in water use, many regions increasingly experience water shortages due to extended dry periods.
- Projected changes in national consumptive water use range from a 9-percent decrease to a 235-percent increase, with the largest impacts resulting from the needs of agriculture in response to climate change.
- Changes in projected aggregate water yield by mid-century range from a 25.7-percent increase under a wet future to a 10.9-percent decrease under a dry future.
- Short-duration droughts are likely to turn into long-duration droughts, and the intensity of drought is likely to increase substantially. Under higher future atmospheric warming, droughts lasting more than a year are projected to occur four times more often and increase in intensity by 76 percent.
- Adaptation options like increased reservoir storage have limited ability to curtail shortage in the long term. Responses to climate change will probably require substantial transfers from agriculture to urban users, which could have serious negative impacts on rural communities.

face increasing water scarcity. Droughts are increasing in frequency and duration, and there is a high amount of uncertainty in future drought characteristics. Whether these trends continue depends on future population growth, sector-specific rates of technology adaptation, and continued changes in regional climatic patterns. Climate models differ in their projected future precipitation patterns, more so than for projections of temperature. Regions that face decreasing water supply and either have large amounts of water use for agriculture or have high population growth are projected to face increasing shortages through the middle of the century. These compounding effects of climate and socioeconomic forces will likely challenge policymakers and force tough decisions about water use among sectors.

Trends in Freshwater Withdrawals: Past and Projected

- Most regions of the United States are expected to see declines or only modest increases in water withdrawals for household use.
- Warmer temperatures due to climate change are projected to increase water use in the energy sector by 20 to 60 percent (1 to 6 billion gallons of water per day)—more than would be needed without climate change.
- Total withdrawals for irrigated agriculture in the conterminous United States are projected to increase from 116 billion gallons in 2015 to 134 billion gallons in 2070 under a hot future.
- Total consumptive use is projected to decrease by as much as 9 percent nationally under a lower warming and moderate population growth future but increase by 235 percent under a high warming and high population growth future, indicating a high level of variation in potential futures and creating challenges for managers hoping to adapt to climate change.

This section of the Resources Planning Act (RPA) Assessment examines trends in past water withdrawals and makes projections for future withdrawals for the conterminous United States, drawing heavily on county-level data from the 5-year U.S. Geological Survey (USGS) water use circulars for which 2015 is the most recent data year (Dieter et al. 2018). Detail is given here for domestic, industrial, irrigated agriculture, and thermoelectric power generation sectors. Together these four sectors make up 72 percent of total water withdrawals in the country (Dieter et al. 2018). Projections of withdrawals extend trends in the USGS data following Brown et al. (2013), which are updated with methods and detailed results in Warziniack et al. (2022). Future projections are developed for the four core RPA scenarios and five climate models (see the sidebar RPA Scenarios). Though not specifically covered in this Assessment, much of this water comes directly from forested lands. Roughly 60 million people depend on forests for more than 50 percent of their water supply (Liu et al. 2021).

Projections of water use rely on three main components: a principal driver, a per-unit rate of withdrawal, and climate feedbacks (table 9-1). Principal drivers (such as population or acres of irrigated agriculture) are first multiplied by the per-unit rate of withdrawal (such as per capita withdrawals for domestic use) to get total freshwater withdrawals absent climate change effects. Rates of withdrawals in some sectors are then adjusted to include climate impacts on water use efficiency, the need for more water in a warmer climate, and changes in water use due to changes in precipitation. Climate feedbacks only affect the per-unit rates of withdrawals and do not address the viability of land to support a given use (e.g., viability of agriculture) or temperature limits on specific uses (e.g., temperature limitations on withdrawing water for thermoelectricity generation).

Table 9-1. Principal drivers, rates of withdrawals, and climate feedbacks used in water use projections.

Sector	Principal driver	Withdrawal rate	Climate impacts
Domestic	Population	Gallons per capita	Changes in summertime precipitation and evapotranspiration impact household outdoor water use
Thermoelectric	Population, total electricity use	Gallons per thermoelectric kWh produced using freshwater	Changes in temperature lead to changes in household and industrial energy demand
Irrigated agriculture	Acres irrigated	Gallons per acre	Changes in growing season precipitation lead to corresponding changes in irrigation demand
Industrial and mining	Personal income	Gallons per dollar income	No climate impacts in model
Livestock and aquaculture	Population	Gallons per person	No climate impacts in model

RPA Scenarios

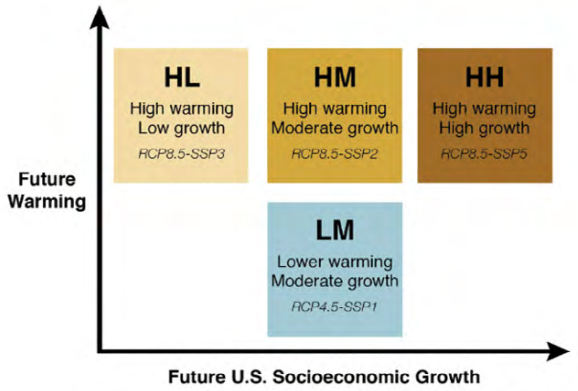
The RPA Assessment uses a set of scenarios of coordinated future climate, population, and socioeconomic change to project resource availability and condition over the next 50 years. These scenarios provide a framework for objectively evaluating a plausible range of future resource outcomes.

The 2020 RPA Assessment draws from the global scenarios developed by the Intergovernmental Panel on Climate Change to examine the 2020 to 2070 time period (IPCC 2014). The RPA scenarios pair two alternative climate futures (Representative Concentration Pathways or RCPs) with four alternative socioeconomic futures (Shared Socioeconomic Pathways or SSPs) in the following combinations: RCP 4.5 and SSP1 (lower warming-moderate U.S. growth, LM), RCP 8.5 and SSP3 (high warming-low U.S. growth, HL), RCP 8.5 and SSP2 (high warming-moderate U.S. growth, HM), and RCP 8.5 and SSP5 (high warming-high U.S. growth, HH) (figure 9-1). The four 2020 RPA Assessment scenarios encompass the projected range of climate change from the RCPs and projected quantitative and qualitative range of socioeconomic change from the SSPs, resulting in four distinct futures that vary across a multitude of characteristics (figure 9-2), and providing a unifying framework that organizes the RPA Assessment natural resource sector analyses around a consistent set of possible world views. The Scenarios Chapter describes how these scenarios were selected and paired; more details are provided in Langner et al. (2020).

The 2020 RPA Assessment pairs these four RPA scenarios with five different climate models that capture the wide range of projected future temperature and precipitation across the conterminous United States. An ensemble climate projection that averages across the multiple model projections is not used because of the importance of preserving individual model variability for resource modeling efforts. The five climate models selected by RPA represent least warm, hot, dry, wet, and middle-of-the-road climate futures for the conterminous United States (table 9-2); however, characteristics can vary at finer spatial scales. Although the same models were selected to develop climate projections for both lower and high-warming futures, there are distinct climate projections for each model associated with RCP 4.5 and RCP 8.5. The Scenarios Chapter describes how these climate models were selected; Joyce and Coulson (2020) give a more extensive explanation.

Throughout the RPA Assessment, individual scenario-climate futures are referred to by pairing RPA scenarios with selected climate projections. For example, an analysis run under "HL-wet" assumes a future with high atmospheric warming and low U.S. population and economic growth (HL RPA scenario), as well as a wetter climate for the conterminous United States (wet climate projection).

Figure 9-1. Characterization of the 2020 RPA Assessment scenarios in terms of future changes in atmospheric warming and U.S. socioeconomic growth. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



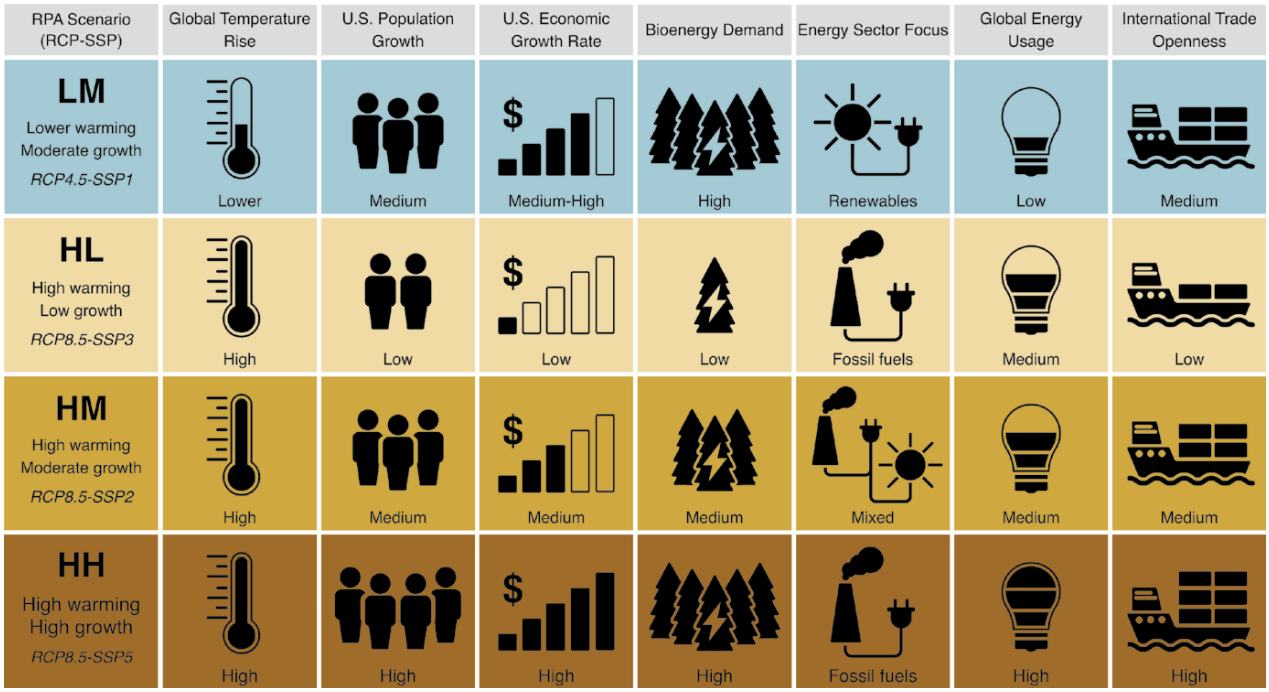
Source: Langner et al. 2020.

Table 9-2. Five climate models selected to reflect the range of the full set of 20 available climate models in the year 2070. Each model was run under RCP 4.5 and RCP 8.5, providing a range of different U.S. climate projections.

	Least warm	Hot	Dry	Wet	Middle
Climate model	MRI-CGCM3	HadGEM2-ES	IPSL-CM5A-MR	CNRM-CM5	NorESM1-M
Institution	Meteorological Research Institute, Japan	Met Office Hadley Centre, United Kingdom	Institut Pierre Simon Laplace, France	National Centre of Meteorological Research, France	Norwegian Climate Center, Norway

Source: Joyce and Coulson 2020.

Figure 9-2. Characteristics differentiating the 2020 RPA Assessment scenarios. These characteristics are associated with the four underlying Representative Concentration Pathway (RCP) – Shared Socioeconomic Pathway (SSP) combinations.



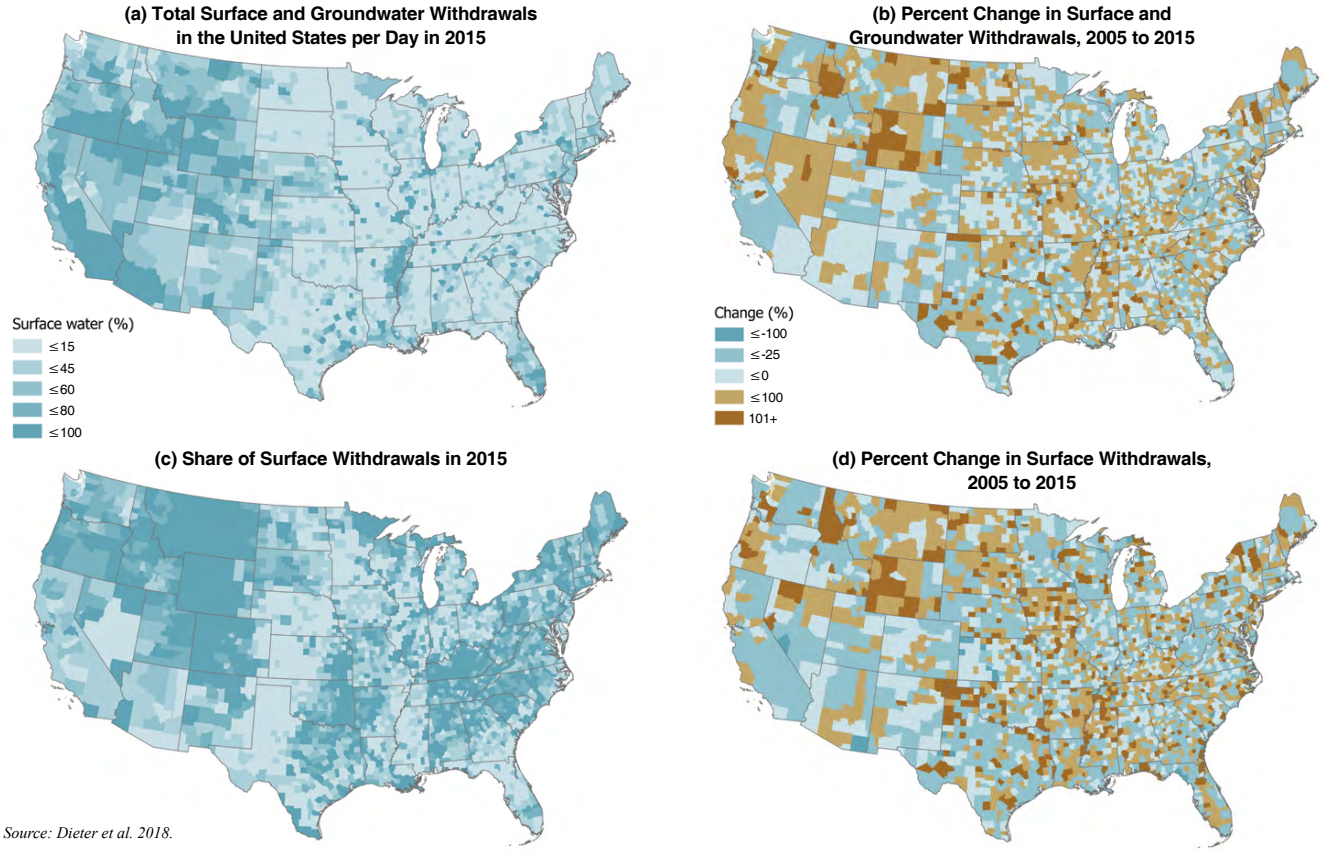
Past Water Withdrawals

Differences in water withdrawals throughout the United States (figures 9-3, 9-4) exist due to historical differences in water abundance, patterns of settlement, agricultural expansion, and industrial development. Agriculture is the largest user of water in most places, accounting for 42 percent of freshwater withdrawals nationally, and is likely to be the driving factor in future water shortages (Dieter et al. 2018, Warziniack and Brown 2019). Many crops require 20 to 30 inches of water per year; areas with precipitation below that amount have to rely on irrigation to successfully farm (Postel 1998). Water for irrigation dominates all other uses in these areas, leading to visual differences in figure 9-3. Comparatively, water withdrawn to produce electricity represents 34 percent of national freshwater withdrawals, and household water use makes up 9 percent of freshwater withdrawals.

Between 2005 and 2015, surface freshwater withdrawals decreased in 64 percent of counties in the conterminous United States to about 322 billion gallons per day (figure 9-3d). During that time, domestic withdrawals for household use fell by 10 percent nationally despite an 8-percent increase in population. Per capita household withdrawals fell from 98 gallons per day in 2005 to 82 gallons per day in 2015. Irrigation withdrawals fell by 7 percent, and thermoelectric withdrawals fell by 34 percent (Dieter et al. 2018).

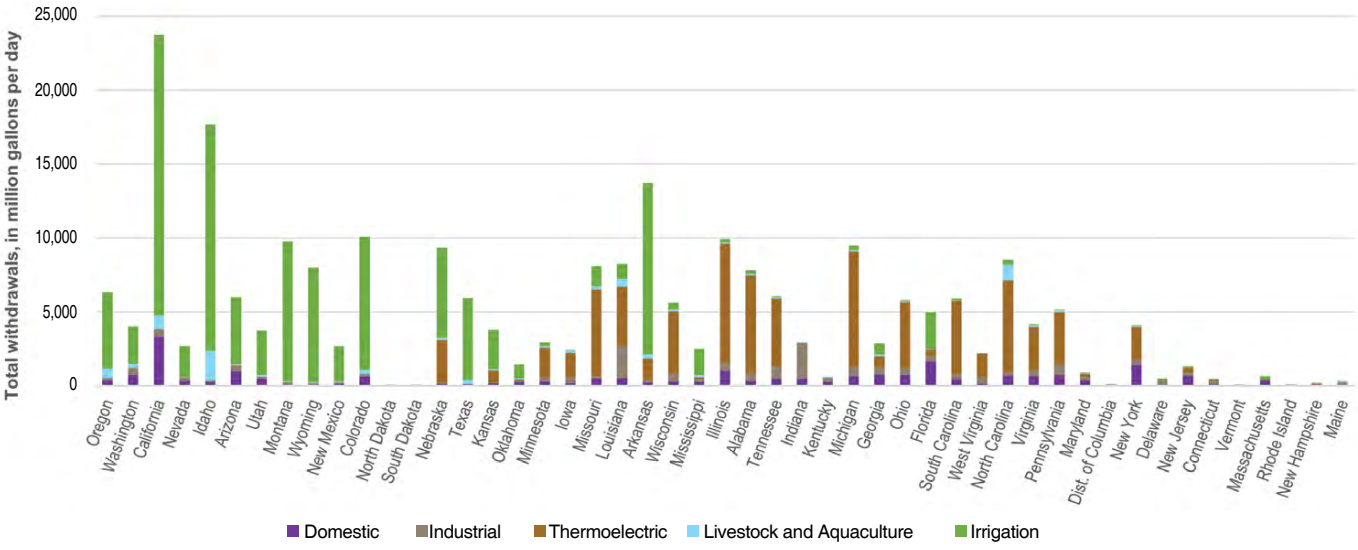
Some of those reductions in water use were necessary due to extreme droughts throughout the last 2 decades. In July 2021, Lake Mead, the largest reservoir in the United States, recorded its lowest water levels since it was filled (BOR 2021). Some reductions, however, have come by way of remarkable improvements in water use technology, including improvements in irrigations methods, increased use of low-flow toilets (the largest in-home use of water), increased use of high-efficiency showerheads and faucets, incentives to reduce outdoor water use, and government policies (Gleick et al. 2009, Lee et al. 2013, Millock and Nauges 2010). The U.S. economy continues to become less water-intensive, as seen by measures like gross domestic product per gallons of water use that have been falling for decades (Dieter et al. 2018, Wang and Hejazi 2011).

Figure 9-3. Freshwater withdrawals (surface and groundwater and share of surface) in 2015 and as percent change from 2005 to 2015.



Source: Dieter et al. 2018.

Figure 9-4. Water withdrawals (surface and groundwater) for each sector by State in 2015. States are ordered from west to east, left to right.



Source: Warziniack et al. 2022, based on data from Dieter et al. 2018.

Projections of Water Withdrawals

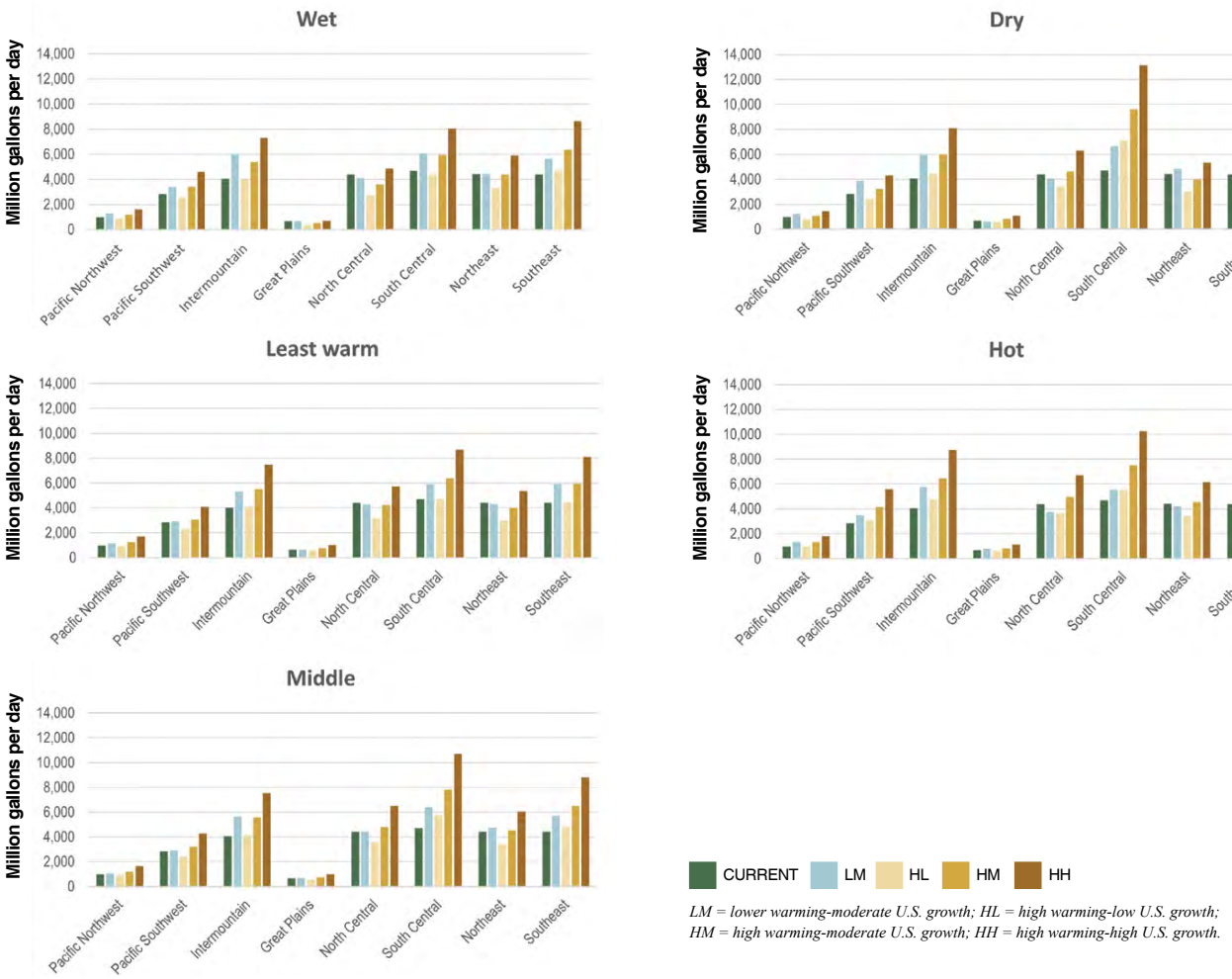
Projections for freshwater withdrawals are described briefly here for the domestic, industrial, and irrigated agriculture sectors. Projections for thermoelectric power generation are for consumptive use instead of withdrawals, making use of new data from USGS. Warziniack et al. (2022) provide more detailed methods as well as projections for all USGS water use sectors out to 2070. The analysis is done at the county scale for the conterminous United States and aggregated to RPA subregions (see figure 2-1 in the Introduction Chapter). Total water withdrawals were 322 billion gallons per day in 2015, of which 198 billion gallons per day were from fresh surface water sources. By 2070, we estimate withdrawals in the conterminous United States will range from a 10-percent reduction under HL-wet (the high atmospheric warming and low socioeconomic change RPA scenario using the wet climate projection) to an over 200-percent increase under HH-hot. Across all RPA scenario-climate futures, there is a mean increase of 47 percent in total withdrawals.

Domestic Water Withdrawals

Domestic water withdrawals are calculated as the product of county population projections and per capita withdrawals, adjusted for impacts on outdoor water use due to climate change. Wear and Prestemon (2019) estimate that U.S. population will increase by 24 to 44 percent under moderate-growth SSPs and by 56 percent under the high-growth SSP5. The fastest growing regions are expected to be in the West and Southwest, which are already facing water stress (U.S. Global Change Research Program 2018) and projected to see populations double under the high-growth SSP5.

Despite these increases, most regions of the United States are expected to see declines or only modest increases in domestic water withdrawals associated with low- and moderate-growth scenarios (figures 9-5, 9-6). In 2015, total withdrawals for domestic use were 26.6 billion gallons per day, of which 23.3 billion gallons per day came from

Figure 9-5. Current (2015) and projected future (2070) domestic withdrawals by RPA subregion and RPA scenario for the five RPA climate projections.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 9-6. Mean percent change from current (2015) to projected future (2070) in domestic water withdrawals across all RPA scenario-climate futures.

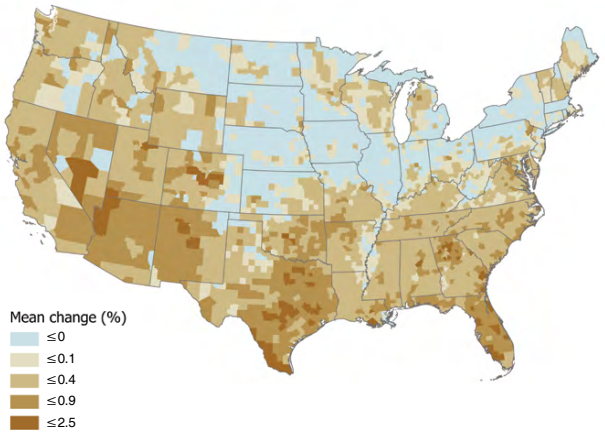
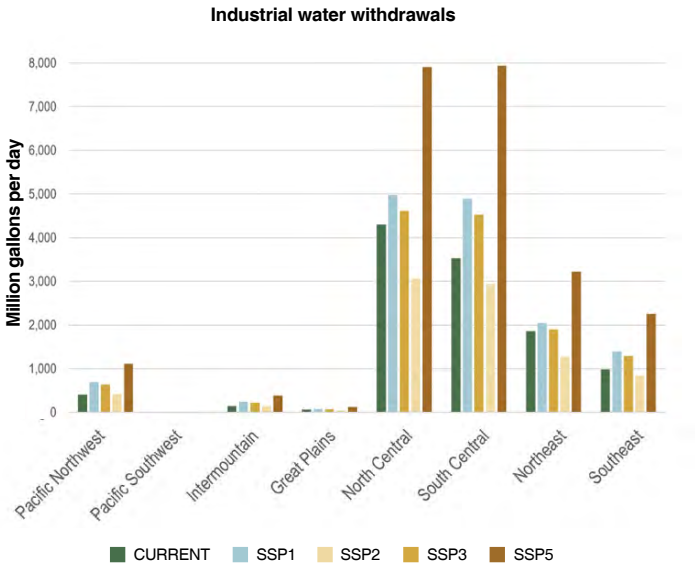


Figure 9-7. Current (2015) and future (2070) industrial withdrawals by RPA subregion. Projections for industrial withdrawals do not have climate feedbacks so only vary by SSP.



SSP = Shared Socioeconomic Pathway.

public suppliers and 3.3 billion gallons per day were self-supplied, largely through wells. Self-supplied surface water withdrawals were only 49 million gallons per day in 2015. In 2070, withdrawals for domestic use in the conterminous United States are projected to range from 22 billion gallons per day to 50 billion gallons per day. In the southern and western parts of the country, rapid population growth is expected to outpace improvements in water use efficiency, leading to increases in withdrawals for domestic use in those regions across all socioeconomic futures. Under high-growth HH-middle, all but 10 counties across the United States are projected to see increases in domestic withdrawals, compared to the low-growth HL, for which 78 percent of counties are projected to see decreases in domestic withdrawals. Because population is the primary driver for domestic demands, SSPs tend to impact projections more than atmospheric warming and climate model selection. The exception is the dry climate projection, particularly for the South Central Subregion, which shows a much larger area of drying centered on Texas and spreading throughout the subregion. Under these conditions, increases in outdoor water use drive large increases in total domestic withdrawals.

Industrial Water Withdrawals

The industrial sector is primarily made up of large users of self-supplied water. Thus, differences in figure 9-7 reflect regional differences in water availability as much as they do regional differences in economic activity. Water withdrawals in the industrial sector range from near zero in the Pacific Southwest to high amounts of withdrawals in the central regions, reflecting regional differences in manufacturing activity and how firms use water (Dieter et al. 2018). For the most part, gains in water efficiency and shifts in the economy toward less water-intensive industries lead to declines in industrial water withdrawals across the country.

Because projections for industrial withdrawals do not have climate feedbacks, results are modeled only using socioeconomic pathways and not using the integrated RPA scenarios or climate models. All regions are projected to see declines in industrial withdrawals for low-growth SSP3 and modest increases under moderate-growth SSPs 1 and 2. All regions are projected to see increases in industrial withdrawals under high-growth SSP5, with noticeable increases in the North Central and South Central Subregions due to the initial size of industry.

Thermoelectric Water Use

Thermoelectric power generation, which represents the largest segment of U.S. electricity production, requires water at several different points in the lifecycle of the generation process, including component manufacturing, fuel acquisition, processing and transport, and power plant operation and decommissioning, but water is primarily used for cooling purposes (Meldrum et al. 2013). Total water withdrawals for power generation peaked in 2010, and water use rates (units of water withdrawn per unit of electricity produced, in gallons/kilowatt hour) have fallen from 22.41 in 1985 to as low as 10.76 in 2015 due to larger adoption of recirculating cooling technologies allowing for greater efficiency in water use.

Estimation of electricity demand for freshwater thermoelectric plants is complicated by the fact that electricity consumed in one basin may be produced in another. A second complication arises because electricity

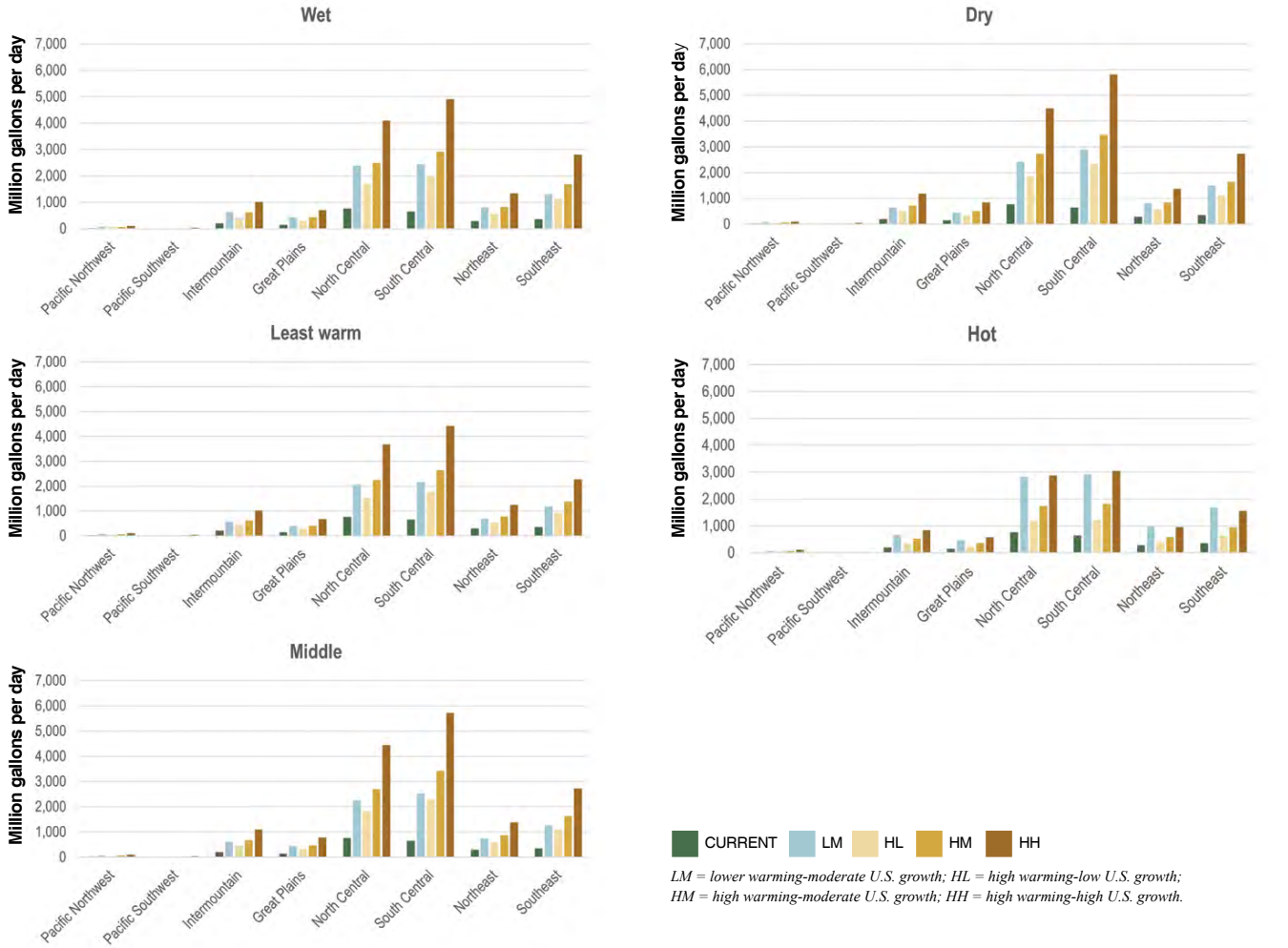
is produced at not only freshwater thermoelectric plants but also at saltwater thermoelectric, hydroelectric, solar, wind, and other types of plants. For projecting future use of freshwater at thermoelectric plants, we estimate growth in thermoelectric production for large energy regions of the United States, subtract the portion of the production to be produced at non-freshwater thermoelectric plants, and apportion the remaining production to each county within respective regions.

Our approach utilizes recently released USGS updated estimates of thermoelectric water use in 2015 (Diehl and Harris 2014, 2019). The new USGS method categorizes thermoelectric plants in the United States that withdraw water based on their methods of generating electricity and disposing of waste heat. The USGS data include consumptive use at the plant level, which we make use of here. Instead of reporting withdrawals and then converting them to consumptive use based on regional averages, this section reports consumptive use directly.

The U.S. Energy Information Administration projects energy consumption to increase 0.3 percent for every 1.9-percent increase in U.S. output (U.S. Energy Information Administration 2020), leading to increases in energy use of 150 percent by 2070 for moderate-socioeconomic growth scenarios (SSP1 and SSP2) and over 400 percent for high-socioeconomic growth scenarios (SSP5). These increases in electricity production lead to increases in water consumption from just under 2.5 billion gallons of water per day in 2015 to between 5 and 17 billion gallons per day in 2070 (figure 9-8).

By 2070, increasing temperatures due to climate change are projected to require 20 to 60 percent more water for electricity production than would be needed without climate change. That increase is equivalent to an extra 1 to 6 billion gallons of water per day needed due to climate change. These projections assume a continuation of past trends in water use efficiency but do not account for large sudden shifts due to changes in policy, new technologies, or fuel types. They also do not account for increasing water

Figure 9-8. Current (2015) and future (2070) thermoelectric consumptive use by RPA subregion and RPA scenario for the five RPA climate projections.



temperatures that might impede cooling at thermoelectric power plants (Van Vliet et al. 2012).

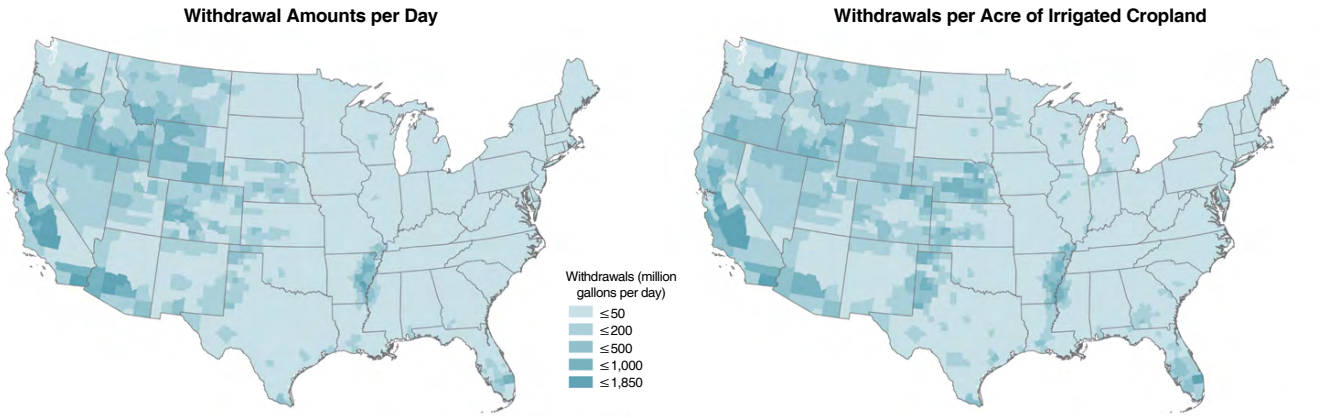
Irrigated Agriculture Withdrawals

Agriculture is the largest user of water nationally, accounting for 42 percent of total freshwater withdrawals. In dry regions like California, agriculture can make up more than 80 percent of total withdrawals. Significant amounts of water are also used for agriculture throughout the southern Mississippi River basin (figure 9-9). In 2015, the 17 Western States accounted for 91 percent of total surface water irrigation withdrawals (Dieter et al. 2018).

Previous water shortages and competition from urban uses have led to decreases in surface water use in the West through reductions in the amount of land irrigated, amount of water applied on any piece of land, and shifts from surface to groundwater supplies. Between 1985 and 2015, irrigation depth on an average acre in the West fell by an annualized rate of 0.85 percent. In the East, however, agricultural water use has increased as farmers use irrigation to offset impacts of more varied precipitation and seek more reliable yields. This analysis assumes rates of change in irrigated acres continue along past trends, as does the amount of water applied to an average acre in each region. Climate impacts are introduced through changes in crop water use due to changes in evapotranspiration; they do not include changes in crop type or growing seasons that might result due to warmer temperatures (Woznicki et al. 2015).

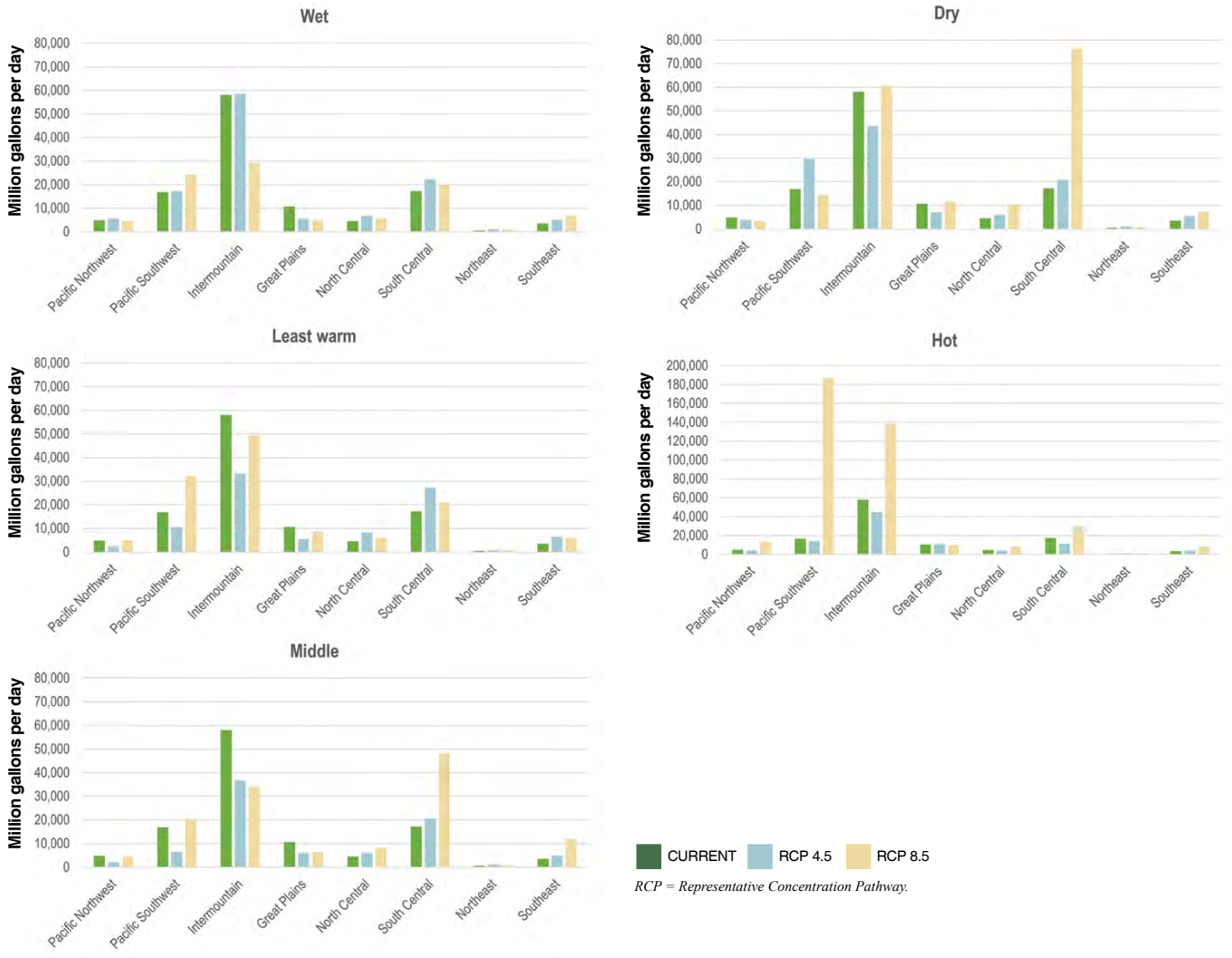
Under the hot climate projection, which represents a worst-case scenario for many of the agricultural regions, total water demanded for irrigation in the United States is projected to increase from 116 billion gallons per day in 2015 to 134 billion gallons per day in 2070 (figure 9-10). The hot climate projection is significantly drier than current conditions in the Pacific Southwest and Intermountain West Subregions, both of which rely on large amounts of irrigation for agriculture. Estimates for agricultural withdrawals do not consider changes in population or income but do include the changes in RCPs 4.5 (lower future warming) and 8.5 (higher future warming), as well as changes in amount of irrigated acreage. SSPs with high population growth are likely to decrease the amount of agricultural acreage faster than historically seen and that are projected here. In such cases, high population growth might decrease agricultural water use if it causes conversion of croplands to development.

Figure 9-9. Agricultural freshwater withdrawals.



Source: 2015 USGS estimates (Dieter et al. 2018).

Figure 9-10. Current (2015) and future (2070) agricultural withdrawals by RPA subregion by climatic pathway (RCP) for the five RPA climate projections. Note the change in scale for the hot climate projection.



RCP = Representative Concentration Pathway.

Projections of Consumptive Use

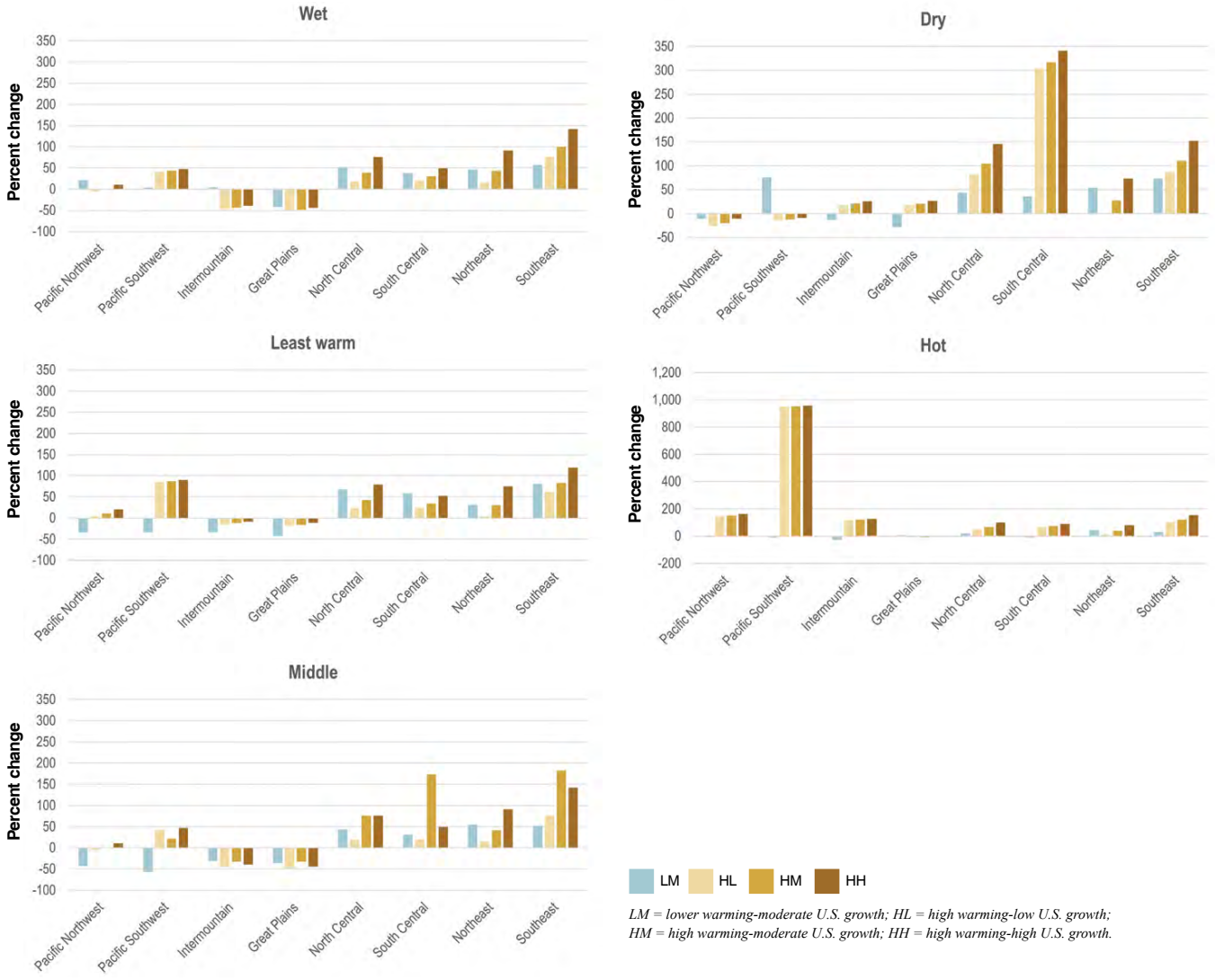
Much of the water withdrawn for human use is returned to the river basin from which it came in the form of runoff and sewage discharge. The portion not returned, and thus not available for downstream uses, is called consumptive use. The USGS estimated consumptive use for irrigated agriculture and thermoelectric power generation in 2015 but only reports withdrawals for other sectors. Nationally, about 62 percent of water withdrawn for agriculture is consumptively used, compared to 3 percent of water withdrawn for power generation (Deiter et al. 2018). Consumptive use for sectors not included in USGS estimates rely on older USGS estimates, dating back to 1990 and 1995 in many cases, and augmented with values from the literature when possible. For those sectors, consumptive use ratios are taken from Brown et al. (2013).

Total consumptive use is projected to fall by about 9 percent under LM-middle and LM-hot, continuing past downward trends in national water use (figure 9-11). Under HH-hot, consumptive use is projected to increase by 235 percent. The Great Plains Subregion sees decreasing consumptive water use for all but the dry climate projection, and the Intermountain Subregion shows decreasing consumptive water use for all but the hot and dry climate projections. The Pacific Northwest sees declines in consumptive use under 9 out of the 20 scenario-climate futures, and for all scenarios using the dry climate projection, which is actually wet for the region (see the Scenarios Chapter sidebar Using Scenarios and Projections in Resource Management Planning). The Pacific Southwest, which sees variation in future precipitation patterns between climate projections and between northern and southern parts of the subregion, sees declines for 6 out of the 20 models. Large increases are projected for the North Central, South Central, and Southeast Subregions, and to a lesser extent in the Northeast. These regions are consistently projected to see increases in consumptive use across all sectors of the economy.

Because agriculture is the dominant use of water in most regions, results often vary by climate projection more than by RPA scenario. Many regions see consumptive use more than double under the climate projections that yield the driest conditions for the respective regions. The most alarming projections across all models and scenarios are for the South Central Subregion, which sees consumptive use rise by over 300 percent under the dry climate projection. These consumptive use projections reflect outcomes if current trends in water use continue. In many cases, such outcomes are not feasible due to limited water supply and highlight areas in which large reductions may be needed.

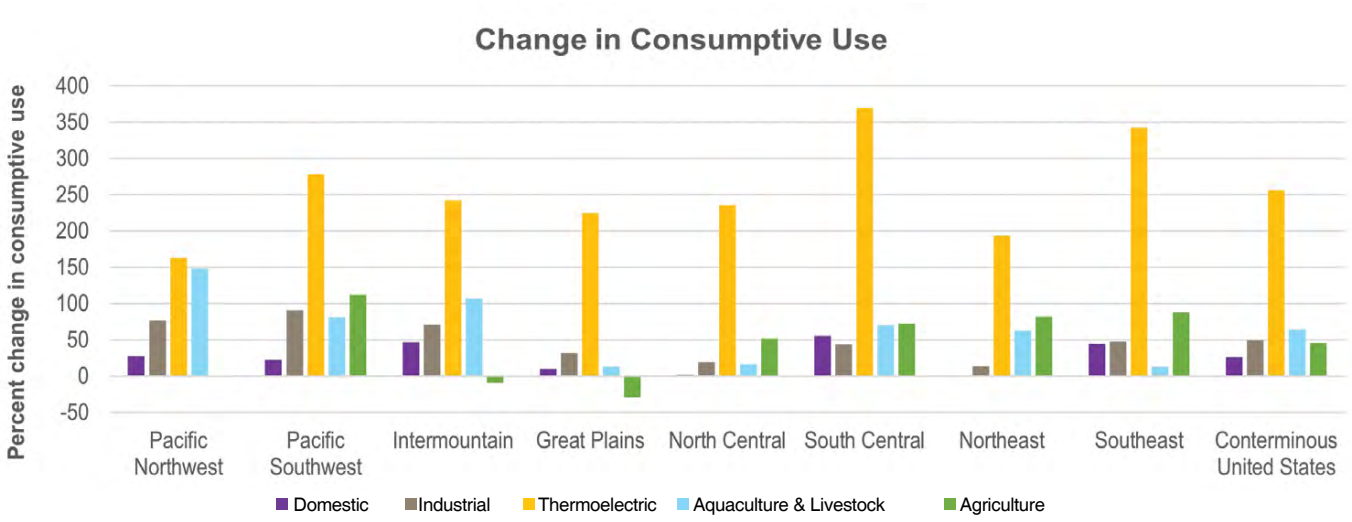
Figure 9-12 shows projected changes in consumptive use by sector. In most regions, projected changes in consumptive use in the domestic sector are relatively modest. Gains in water use efficiency have mostly kept up with increases in population. Consumptive use in the agricultural sector is highly variable, with decreases on average in the Great Plains and Intermountain Subregions. The largest percentage increases are projected in thermoelectric power generation. Adaptation in cooling technologies have led to improvements in the sector, but for this analysis, population and economic growth outpace historic rates of change. These results could be interpreted a few ways. Trends in the analysis reflect trends in per capita energy use and water used for an average kilowatt of energy produced; these estimates may miss sudden shifts in technology. However, the largest increases in water use for the thermoelectric generation sector are projected for the central regions of the United States. These regions drive much of the national results and have not seen as widespread adoption of more efficient cooling technologies.

Figure 9-11. Change in total consumptive use by RPA subregion and RPA scenario for the five RPA climate projections. Note the change in scale for the hot climate projection.



LM = lower warming-moderate U.S. growth; HL = high warming-low U.S. growth; HM = high warming-moderate U.S. growth; HH = high warming-high U.S. growth.

Figure 9-12. Mean changes in consumptive use by sector and RPA subregion from 2015 to 2070, across all scenario-climate futures.



Trends in Water Yield: Past and Projected

- Changes in water yield across the conterminous United States range from a 25.7-percent increase under a wet future to a 10.9-percent decrease under a dry future.
- The most consistent results across climate futures are increases in precipitation and yield for much of the Western United States, decreases in the Southwest, and decreases in the South.
- Many Eastern States receive more than 50 percent of their water from forested lands. Western States receive smaller shares of water from forests, but what water does come from forests overwhelmingly comes from national forests.

Hydrological responses to climate variability and change were assessed for the current (1986 to 2015) and mid-century (2041 to 2070) periods. The Variable Infiltration Capacity (VIC) model (Liang et al. 1994) was used to simulate hydrological responses. The model is a macroscale semi-distributed hydrological model that simulates land-atmosphere fluxes and water and energy balances at the land surface (Cherkauer and Lettenmaier 2003). Water yield represents discharge at the watershed outlet and includes both surface runoff and groundwater contributions. River storage and routing are not included in the model. In this section, yield is differentiated from supply, which is used in the next section on storage. Water yield is a function of precipitation and evapotranspiration within a watershed. Water supply includes water yield as well as increases and decreases due to water diversions between watersheds.

The current RPA study improves on spatial and temporal scales compared to past RPA water assessments. It utilizes an enhanced version of the VIC model that resolves hydrological processes at the 4- x 4-km grid resolution and daily time steps to project water yield and evapotranspiration based on bias-corrected and downscaled regional climate inputs. The analysis also incorporates improved parameterization of various model components for river basins across the conterminous United States (Naz et al. 2016, Oubeidillah et al. 2014). Hydrological responses are subsequently aggregated at the 8-digit hydrologic unit code (HUC 8) watershed scale for water shortage assessments (Heidari et al. 2021). Water yield from forested lands, including national forests, is shown by State in the sidebar Water Yield from Forests.

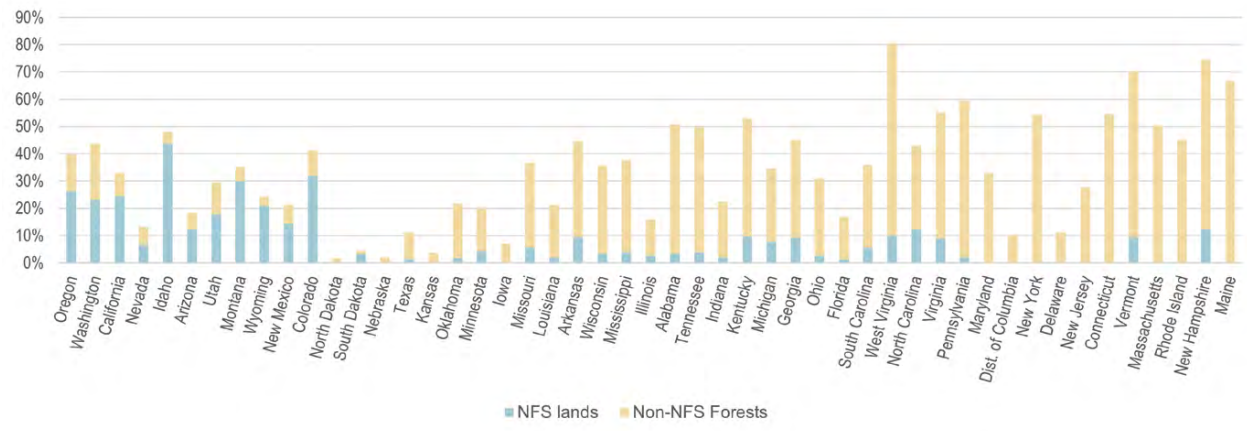
Current (1986 to 2015) daily precipitation and temperature are derived from Daymet (Thornton et al. 1997) and PRISM (Daly et al. 2008) datasets. The North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006) is used to obtain historical wind-speed data. Future climate conditions are characterized across pathways of climatic change associated with atmospheric warming (RCPs 4.5 and 8.5), using the five climate models described in the sidebar RPA Scenarios (table 9-1), selected to span least warm, hot, dry, wet, and middle climate conditions across the conterminous United States. These climate projections are used to

Water Yield from Forests

Forests play an important role in the provision of water, both because they provide high percentages of many States' total water yield and because the water from forests is generally more reliable and of higher quality than for other land uses (Ellison et al. 2017, Liu et al. 2021). Figure 9-13 shows percent of water yield from forested lands based on current conditions used in this assessment. Across the conterminous United States, 39 percent of water originates from forests, and 15 percent originates from national forests and grasslands. Many Eastern States receive more than 50 percent of their water from forested lands. West Virginia gets about 80 percent of its water from forests, followed by New Hampshire and Vermont with 74 and 70 percent, respectively. Western States receive smaller shares of water from forests, but what water does come from forests overwhelmingly comes from national forests. Idaho gets 44 percent of its water from national forests, a larger percentage than any other State. Colorado and Montana get 32 and 30 percent of their water from national forests, respectively.

Whether forests can continue to provide reliable water in a future with climate change is an important research question. National forests and grasslands are likely to experience larger changes in hydroclimatic conditions compared to the other lands within the conterminous United States (Heidari et al. 2021). Under the high atmospheric warming pathway and the dry, middle, and wet climate projections, national forests in mountainous regions are likely to have larger changes in water yield and other hydroclimatic conditions than other regions. Among U.S. Department of Agriculture, Forest Service management regions, the Southwestern Region is likely to experience the largest shifts in water yield and hydroclimatic characteristics. The Southern Region is likely to become more arid with significant decreases in water yield under the dry climate projection. The Pacific Southwest and Intermountain Regions are likely to become less arid and see increases in water yield. Water yield from national forests in the Pacific Northwest is likely to decline under all climate projections despite the projected increase in precipitation.

Figure 9-13. Percent of water yield in each State from forests and national forests, ordered from west to east.



assess shifts in hydrological responses and hydroclimatic conditions. Land use is represented by historical conditions and is held constant over the assessment period.

Precipitation, Water Yield, and Potential Evapotranspiration

In general, precipitation is higher in the Eastern United States, leading to higher water yield, while potential evapotranspiration is higher in the Southwestern United States (figure 9-14). By mid-century, changes in aggregate water yield across the conterminous United States range from a 25.7-percent increase under the wet climate projection to a 10.9-percent decrease under the dry climate projection. Figures 9-15, 9-16, and 9-17 show changes in the spatial patterns of precipitation, water yield, and potential evapotranspiration (PET) under the five selected climate projections and two pathways of climatic change for mid-century (2041 to 2070). The projections show high variability. In the South, Southeast, and Great Plains, the dry climate projection shows decreases in water yield, whereas the wet and hot projections show increases in water yield

Figure 9-14. Precipitation, water yield, and potential evapotranspiration for the baseline period (1986 to 2015).

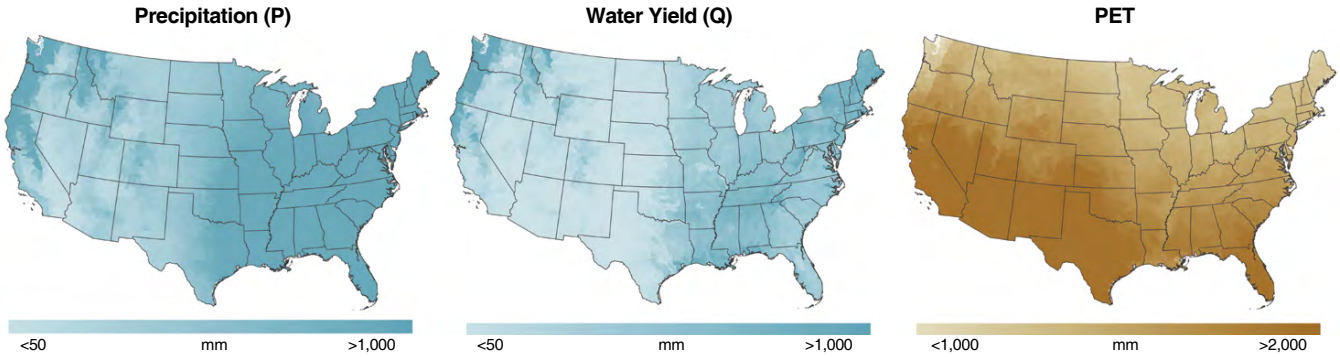
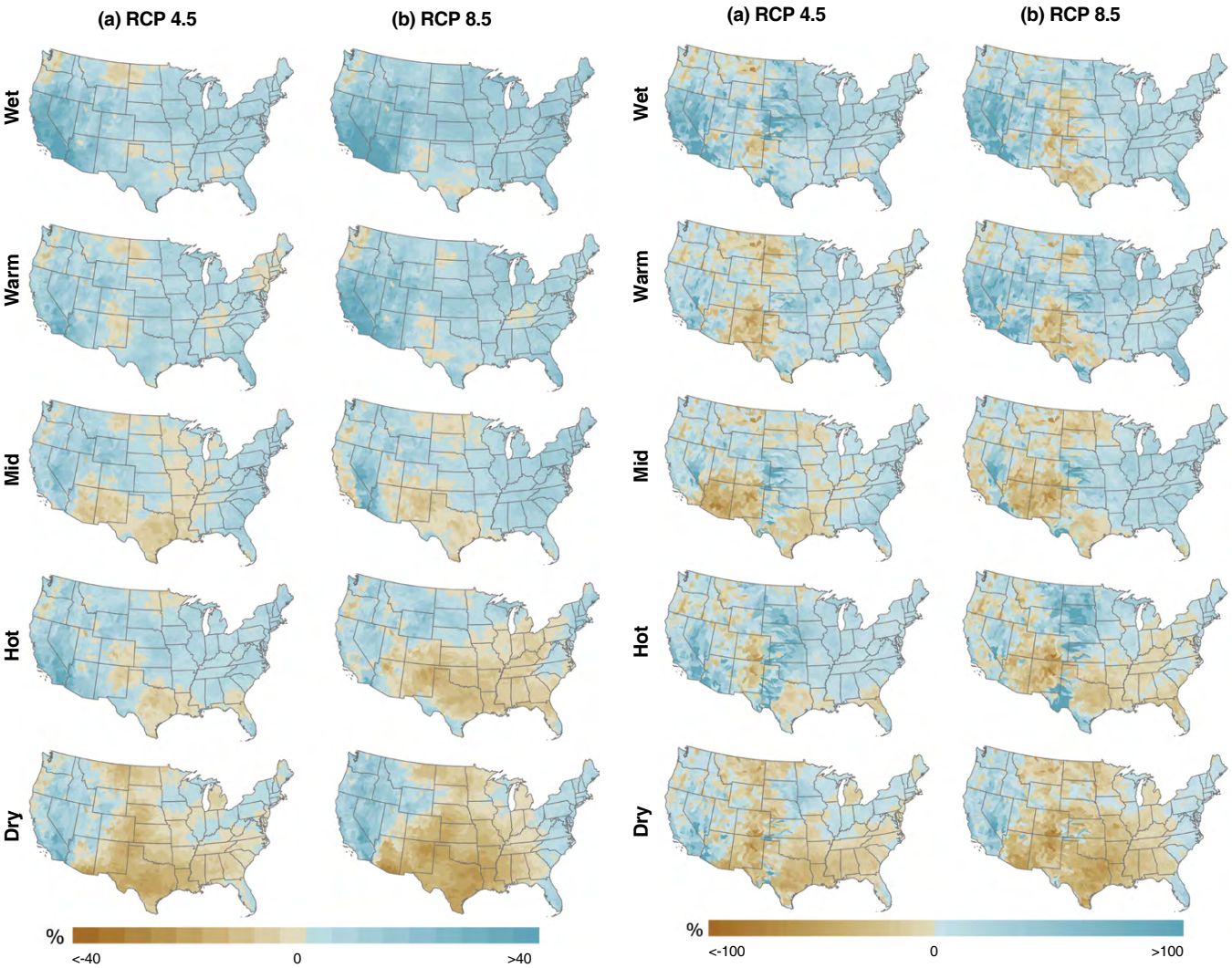


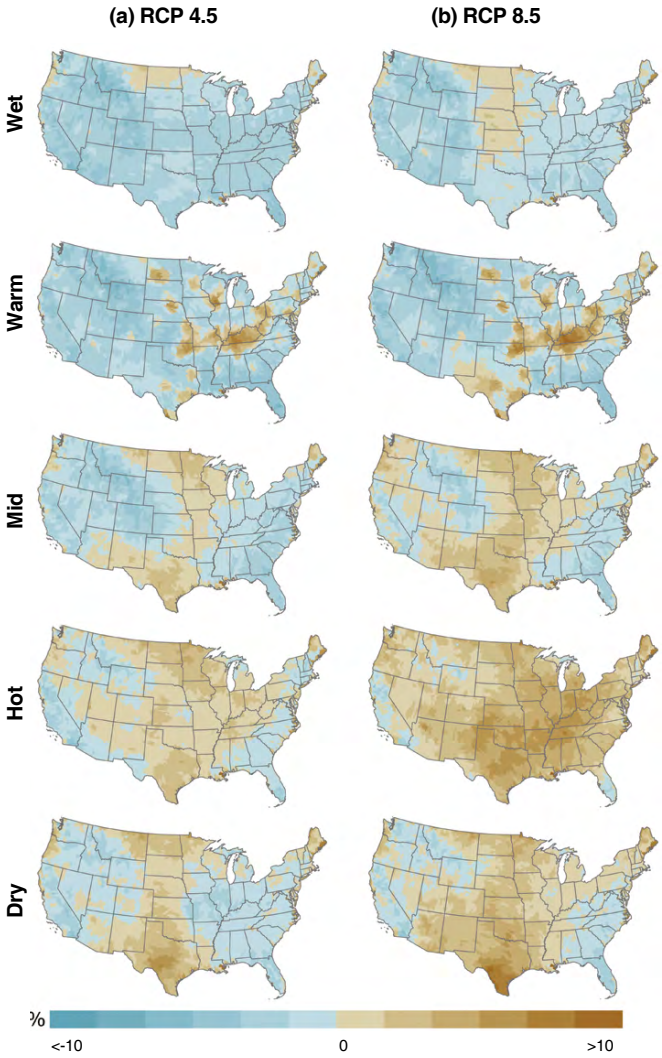
Figure 9-15. Spatial changes in 30-year average of annual precipitation in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.

Figure 9-16. Spatial changes in 30-year average of annual water yield in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.



for these same subregions. The most consistent results across projections are increases in precipitation and yield for much of the Western United States and decreases in water yield in the Southwest (figures 9-14 and 9-15). Much warmer temperatures in the South are projected to increase potential evapotranspiration more than for any other region, amplifying the effects of decreased precipitation and leading to further declines in water yield (figure 9-16). The majority of river basins in the Western United States are projected to experience a decrease in potential evapotranspiration under the wet and least warm climate projections but increases in potential evapotranspiration under the hot, dry, and middle projections. Large increases in potential evapotranspiration occur in the southern parts of the Great Plains and North Central Subregions.

Figure 9-17. Spatial changes in 30-year average of annual potential evapotranspiration (PET) in response to future climate change, from current (1986 to 2015) to mid-century (2041 to 2070) for: (a) RCP 4.5 and (b) RCP 8.5.



Vulnerability to Water Shortage and Socioeconomic Drought

- Extended dry spells turn short-term water shortages into intense long-term shortages.
- Under high future warming, droughts lasting more than a year are projected to occur four times more often and increase in intensity by 76 percent.
- Medium-intensity droughts will occur six times more often and severe droughts will be 76 percent more severe by 2070 under RCP 8.5, relative to current conditions.

Water shortage occurs when demands are partially or fully unmet, a condition also referred to as socioeconomic drought, or just drought, for the purposes of this chapter. Droughts are typically characterized by their magnitude, duration, frequency, and intensity. Magnitude is the cumulative deficit over the duration of the drought; duration is the number of consecutive periods in drought; frequency is the expected arrival time (i.e., return period) of the drought; and intensity is computed by its magnitude divided by its duration (essentially the average magnitude of the drought). The drought return period represents how likely a drought of that magnitude is in any given year. For example, a 10-year drought would be expected to occur about once every 10 years, or that there is a 10-percent chance of such a drought happening in any given year. Similarly, a 100-year drought would be expected to occur about once every 100 years, or that there is a 1-percent chance of such a drought happening in any given year. In terms of categorizations, 10-year droughts are considered medium intensity, whereas 100-year droughts are considered severe. Similar descriptions are commonly used for floods (that is, 100-year floods or 50-year floods) to create flood zone maps.

Methods for modeling water supply and shortage follow Brown et al. (2013). They rely on projections of consumptive water use (Brown et al. 2019), water yield (Heidari et al. 2020b), stream networks, reservoir storage capacity within each river basin, instream flow requirements, and trans-basin water systems and transfers. Water supply in this section differs from water yield in the above section in that water supply includes trans-basin diversions. Instream flow requirements are also included here as a demand requirement. Water is routed through stream networks and diversions using a Water Evaluation and Planning (WEAP) model for the conterminous United States (Sieber et al. 2002). The WEAP model is run at the monthly time scale, and shortage occurs when demand (the sum of consumptive use and instream flow requirements) exceeds water supply.

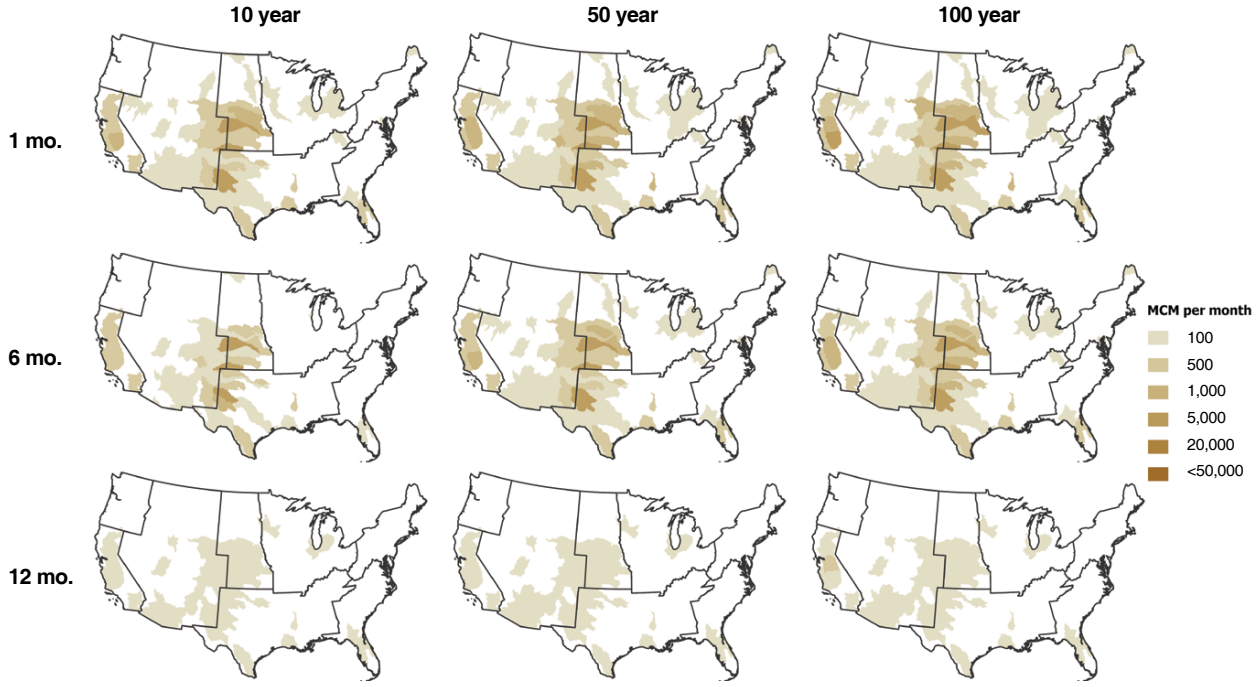
Distributions of shortages from the WEAP results are used to calculate statistical likelihoods of shortage and expected durations and frequency of drought following Heidari et al. (2020a, 2021). This analysis improves previous RPA water assessments by using a monthly rather than annual time step that allows analysis of droughts with duration less than a year (sometimes called flash droughts) and droughts with duration more than a year but not necessarily in annual increments.

Figure 9-18 shows current (1986 to 2015) shortage frequencies, durations, and intensities for HUC 4 basins across the country. Much of the United States currently experiences at least moderate shortages. The southern Great Plains and Rocky Mountain Subregions, southern California, and northern Florida already experience high-intensity shortages of less than a month in length as well as relatively less intense shortages with duration equal or greater than 6 consecutive months.

Future shortages for the lower and high-atmospheric warming futures (RCPs 4.5 and 8.5, respectively) using the dry climate projection are shown in figures 9-19 and 9-20; these projections represent a worst-case scenario for many regions of the conterminous United States. Under the dry climate projection, conditions worsen for much of the central United States. The most consistent increases in intensity and frequency of both within-year (duration less than 12 months) and over-year (duration great than 12 months) shortages occur in the southern portion of the Great Plains. In many places, extended dry spells turn short-term shortages into long-term intense shortages, including the middle Great Plains, Southwest, and South. This pattern extends into the southern Rocky Mountains with lower intensity, as well as the North Central Subregion, which currently only experiences low-intensity shortages. Conditions are projected to improve slightly for northern Florida under RCP 4.5 but deteriorate significantly under RCP 8.5, especially for extended shortages. Although climate projections were selected to represent conditions across the entire conterminous United States, precipitation under the RPA dry climate projection is expected to increase in much of the west coast, resulting in less frequent shortages.

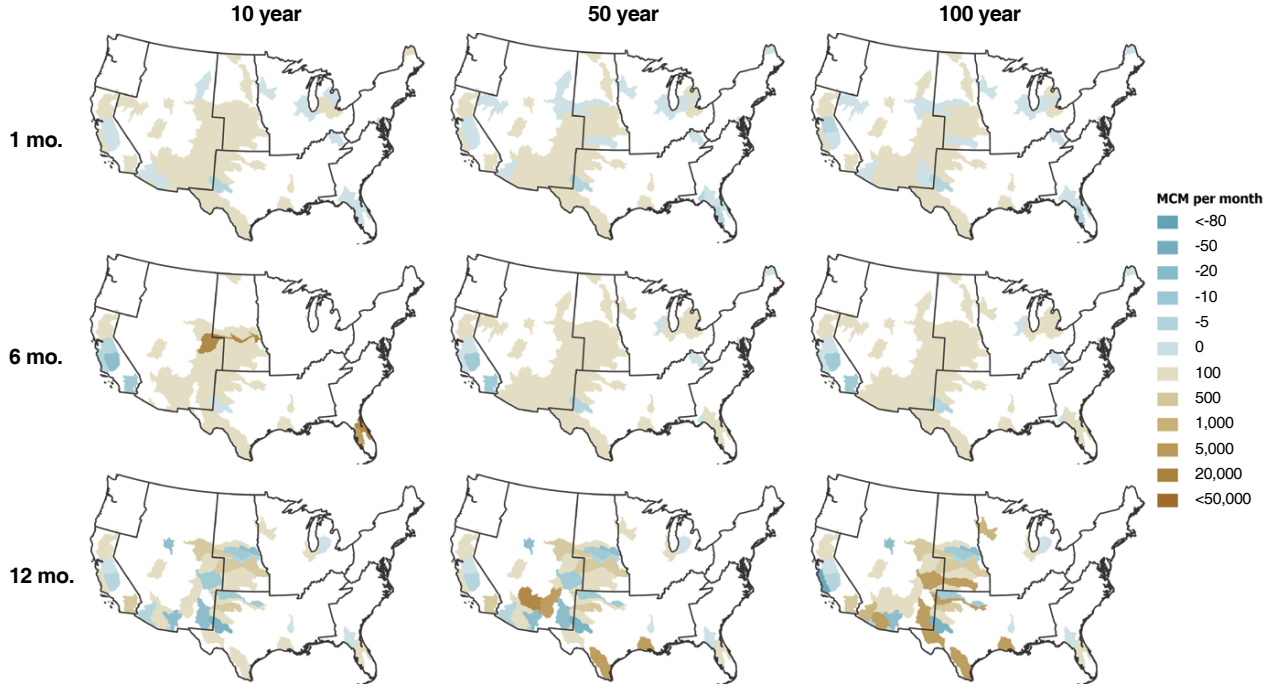
In many places, infrequent extreme droughts are projected to become more frequent, and the duration of droughts is projected to become longer. Droughts that currently last 1 month turn into 6-month droughts, and droughts that currently last 6 months turn into 12-month droughts. The intensity of droughts that are projected to occur in the future period every 10, 50, and 100 years also increases. What would currently be considered a 10-year drought is expected to occur 2.5 times more often under RCP 4.5 and 6 times more often under RCP 8.5, with increases in intensity and

Figure 9-18. Intensities of water shortage events under the current conditions (1986 to 2015) in million cubic meters per month. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought).



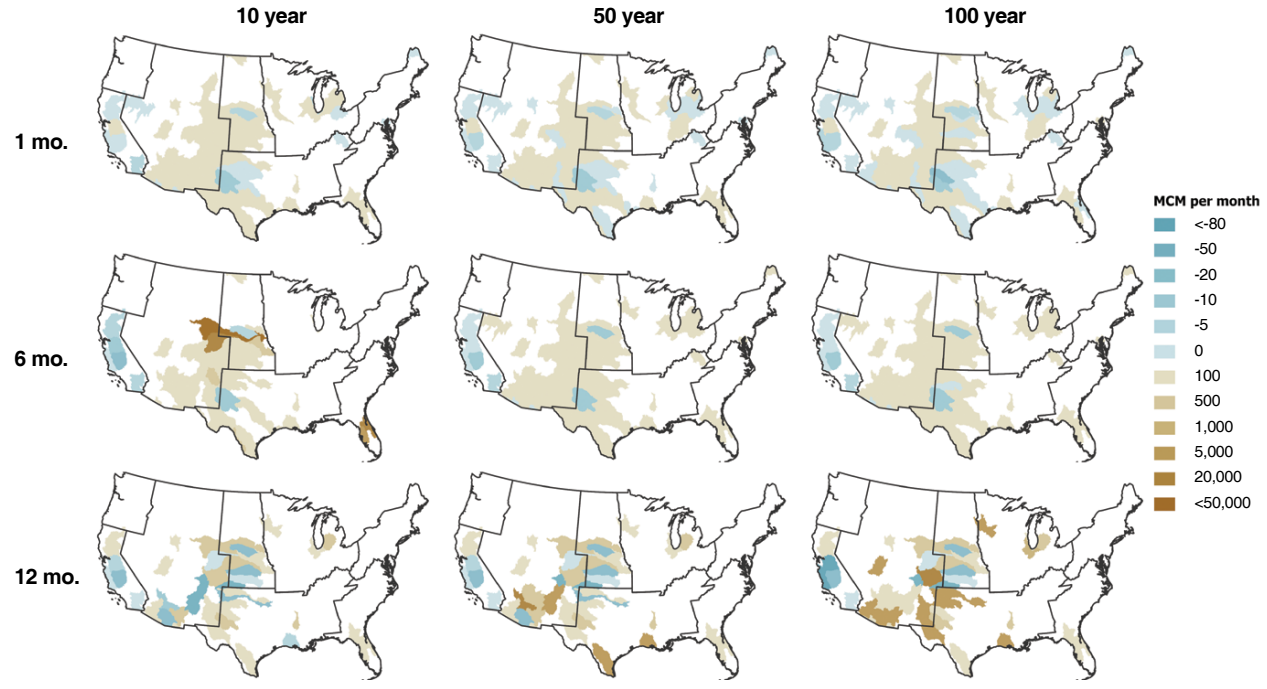
MCM = million cubic meters.

Figure 9-19. Changes in the intensities of water shortage events from current (1986 to 2015) to future (2041 to 2070) conditions under RCP 4.5. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought). Locations mapped in brown are projected to experience increasing water shortage intensities, while locations mapped in blue are projected to experience decreasing shortage intensities relative to current shortage conditions.



MCM = million cubic meters; RCP = Representative Concentration Pathway.

Figure 9-20. Changes in the intensities of shortage events from current (1986 to 2015) to future (2041 to 2070) conditions under RCP 8.5. Shortage duration increases moving from top to bottom (duration greater than 1 month, greater than 6 months, greater than 12 months). Shortage return-period increases moving left to right (10-year drought, 50-year drought, 100-year drought). Locations mapped in brown are projected to experience increasing water shortage intensities, while locations mapped in blue are projected to experience decreasing shortage intensities relative to current shortage conditions.



MCM = million cubic meters; RCP = Representative Concentration Pathway.

frequency occurring in the Great Plains, Intermountain, North Central, South Central, and Southeast Subregions. Droughts decrease in frequency in parts of the Pacific Southwest due to the relative wetness of the dry climate projection in southern California. Hundred-year droughts (those with 1-percent likelihood in any given year) that last longer than a year are projected to increase in intensity by 27 percent under RCP 4.5 and by 76 percent under RCP 8.5.

Management Implications

In August 2021, the U.S. Department of the Interior declared the first-ever Colorado River Basin water shortage, triggering a series of water use reductions according to a drought contingency plan that was approved by Congress in 2019. Under the contingency plan, Arizona will lose 18 percent of its annual allocation of Colorado River basin water in the 2022 water year, representing 8 percent of the State's total water use; Nevada will lose 7 percent of its Colorado River basin water. These cuts fall heavily on agriculture in affected States, where farmers and ranchers rely on irrigation to support their livelihoods. In many cases, farmers have responded to water shortages and drought by increasing their use of groundwater, often at rates that exceed aquifer recharge rates (Hornbeck and Keskin 2014, Medellín-Azuara 2016). According to many of the projections in this assessment, such impacts on incomes, lifestyles, and other natural resources will become more common.

One of the key insights for management is that average future water yields are highly uncertain, but more frequent and intense droughts are likely. Based on these insights, we recommend that managers prepare for a more variable future, developing drought management plans and promoting conservation practices among water users. Our projections assume water use continues according to past trends, and thus highlight where adaptation may be needed as opposed to identifying where shortages may occur in the future. In regions where water becomes more scarce, economic pressure will likely shift water use between sectors and regions (Blanc et al. 2014). Longer term responses to climate change might require substantial transfers from agriculture to urban users, which could have serious negative impacts on rural communities (Brown et al. 2019, Warziniack and Brown 2019). Increasing reservoir storage might provide short-term relief but ultimately relies on sufficient water yield to fill the reservoirs, an increasing problem throughout the country (Brown et al. 2019). Reservoir levels may become low enough to affect hydroelectric power productions (Craig et al. 2018, Boehlert et al. 2016, Henderson et al. 2015).

Low flows in river systems due to climate change and human uses are already affecting aquatic biota and ecosystems, with compounding effects on water quality and temperature. More details on current and future conditions of aquatic species are discussed in the Biodiversity Chapter. The results from that chapter highlight the broad suite of risks to aquatic systems, from climate change, low flows, and development pressures, and point to the role Federal lands may play in preserving critical ecosystem services and providing refugia to threatened species.

Not all news related to water resources is bad. In many places, conservation efforts have reduced total water demand, even in areas with significant population increase. Innovative programs by local water managers have led to large reductions in household water use. Nevada, for example, recently passed a law restricting irrigation of lawns, or "nonfunctional turf" (Assembly Bill 356). Los Angeles' Metropolitan Water District offers $1 per square foot of lawn turf removed from residential properties. Similar policies that either impose restrictions or provide incentives to reduce turfgrass are likely to become more common.

Conclusions

Much of the country has made and will continue to make improvements in water use efficiency, leading to declines in total withdrawals. However, water use continues to increase in areas with rapid population growth and expanding agriculture. Many of these regions are already facing regular water shortages. Whether shortages increase in the future depends heavily on the climate outcome. Projected changes in national consumptive water use range from a 9-percent decrease to a 235-percent increase, with the largest impacts resulting from the needs of agriculture in response to changes in precipitation and aridity. These results highlight a conundrum associated with climate change and water use—a drier climate leads to increases in water demand. By mid-century, changes in aggregate water yield across the conterminous United States range from a 25.7-percent increase under the wet climate projection to a 10.9-percent decrease under the dry climate projection.

Water shortages are consistently projected to increase in intensity, frequency, and duration in the Southwest and Great Plains Subregions. If water yield decreases as projected due to climate change and shortages become longer and more frequent, these results suggest a mix of supply and demand adaptation measures may be needed. Common solutions like groundwater mining and transfers of water from the agricultural to the domestic sector will work in some but not all cases (Brown et al. 2019, Warziniack and Brown 2019). Novel adaptation methods may eventually be needed, such as increased use of recycled water, expanded use of precision agriculture, more efficient water pricing and transfers, and updated water infrastructure (Gleick 2016).

Projections of water use given here assume continuation of recent trends in economic production and water use

efficiency. They are not bound by how much water is actually available nor do they consider changes in water scarcity and competition between sectors. Estimates of withdrawals and consumptive use are therefore likely to be larger than those produced with models that maximize the value of water subject to total water availability (e.g., Draper et al. 2003, Pulido-Velazquez et al. 2008) and models that estimate water requirements needed to maintain current practices in a future with climate change (e.g., Marston et al. 2020, Strzepek et al. 2012). 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.

Uncertainty exists around these projections, highlighted by the varied results for water yield across climate projections, but also due to underlying assumptions about socioeconomic factors like population growth and technological adaptation. Because demand cannot exceed supply, adjustments and mitigation measures may be needed. The RPA Assessment attempts to capture the full range of plausible future conditions to highlight where models agree and where large amounts of uncertainty exist, to help managers plan for the worst-case scenario.

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