RECLAMATION

Managing Water in the West

SECURE Water Act Section 9503(c)—Reclamation Climate Change and Water 2016

Chapter 2: Hydrology and Climate Assessment

U.S. Department of the Interior
Bureau of Reclamation

March 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

SECURE Water Act Section 9503(c) 2016 Report to Congress

Chapter 2: Hydrology and Climate Assessment

Prepared for

United States Congress

Prepared by

U.S. Department of the Interior
Bureau of Reclamation

U.S. Department of the Interior
Bureau of Reclamation
Policy and Administration
Denver, Colorado

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Acronyms and Abbreviations

CCAWWG	Climate Change and Water Working Group
CIRES	Cooperative Institute for Research in Environmental Sciences
CMIP	Coupled Model Intercomparison Project
ESRL	Earth System Research Laboratory
GWRP	Groundwater Resources Program
MAF	million acre-feet
M&I	municipal and industrial
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Survey
NWC	National Water Census
Reclamation	Bureau of Reclamation
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WAUSP	Water Availability and Use Science Program
WCRP CMIP5	World Climate Research Program's Coupled Model Intercomparison Project phase 5
WWCRA	West-Wide Climate Risk Assessment

About this Chapter

This summary chapter is part of the 2016 SECURE Water Act Report to Congress prepared by the Bureau of Reclamation (Reclamation) in accordance with Section 9503 of the SECURE Water Act. The 2016 SECURE Water Act Report follows and builds on the first SECURE Water Act Report, submitted to Congress in 2011[1], which characterized the impacts of warmer temperatures, changes to precipitation and snowpack, and changes to the timing and quantity of streamflow runoff across the West.

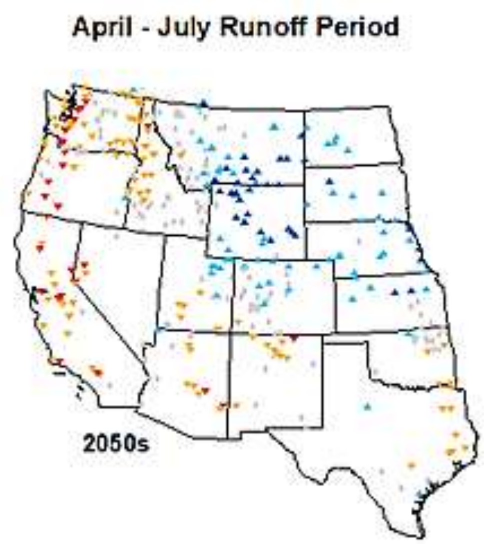
This chapter provides an updated summary of west-wide climate and hydrology projections and is organized as follows:

Section 1: Introduction to Reclamation's hydrology and climate assessments,

Section 2: Assessment of the effects and risks resulting from global climate change on water supply,

Section 3: Assessment of increases in water demand as a result of increasing temperatures and the rate of reservoir evaporation,

Section 4: Brief overview of coordination with the U.S. Geological Survey (USGS) to analyze groundwater supply and climate change impacts, and



Projected change in April-July runoff for the 2050s relative to the 1990s (See Figure 2-5)

Section 5: Coordination activities to strengthen the understanding of water supply trends through research activities.

The key studies referenced in this chapter include west-wide assessments of water supply and demand projections. Additional information specific to each western river basin, including the strategies developed to address potential water shortages, is included in Chapters 3 through 10.

[1] The first SECURE Water Act Report, submitted to Congress in 2011 is available on the Reclamation website here: www.usbr.gov/climate/secure/docs/2011secure/2011SECUREreport.pdf

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1 Introduction

In meeting its mission, Reclamation's planning and operations rely upon assumptions of present and future water supplies based on climate. Water supply and water management are critical areas projected to be impacted by future climate conditions. Climate change adds to historic water challenges in the western United States (U.S.), not necessarily introducing new challenges, but adding additional stress to water supplies and resources already stretch to, or beyond, natural limits (Dettinger et al., 2015).

To assess the risk and impacts to water management and its operations, Reclamation is conducting West-Wide Climate Risk Assessments (WWCRA) to develop important baseline information about climate changes risks for western U.S. water supplies, water demands, and related conditions that influence water management. Reclamation's assessments are consistent with the key findings from the Third National Climate Assessment (Melillo et al., 2014) with respect to water supply that include:

- **Changing Rain, Snow, and Runoff:** Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous U.S.
- **Droughts Intensify:** Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.
- **Increased Risk of Flooding in Many Parts of the U.S.:** Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline. Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.
- **Groundwater Availability:** Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge—reducing groundwater availability in some areas.
- **Risks to Coastal Aquifers and Wetlands:** Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.
- **Water Quality Risks to Lakes and Rivers:** Increasing air and water temperatures, more intense precipitation and runoff, and intensifying

droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

- **Changes to Water Demand and Use:** Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.
- **Water Supply Availability:** Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.
- **Water Resources Management:** In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices. In many places, competing demands for water create stress in local and regional watersheds.

This chapter describes Reclamation's climate and hydrology assessments that were conducted to collectively summarize the effect of global climate change on water resources in each major Reclamation river basin.

2 West-Wide Water Supply Assessment

Within water management planning, climate informs estimations of future water supplies, future water demands, and boundaries of system operation. In meeting its mission, Reclamation relies upon assumptions of present and future water supplies based on climate. The following section provides an overview of projected future climate and hydrology conditions. This information serves as an update to the climate projections presented in the 2011 SECURE Water Act Report to Congress using the most recent climate and hydrology projections available.

2.1 West-wide Climate and Hydrology

Climate information influences the evaluation of resource management strategies through assumptions or characterization of future potential temperature, precipitation, and runoff conditions among other weather information. Water supply estimates are developed by making determinations of what wet, dry, and normal periods may be like in the future and include the potential for hydrologic extremes that can create flood risks and droughts. Risks to future water supplies presented in this section are based on the West-Wide Climate Risk Assessments: Hydroclimate Projections Technical Memorandum (Reclamation, 2016 [Projections]).

The assessment involved developing hydrologic projections associated with a large collection of the global climate projections featured in the IPCC Fifth Assessment (IPCC, 2013) and developed as part of the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project (CMIP5) phase 5.[2] CMIP5 projections are regarded as the most recent project data available for describing future global climate possibilities. Additional information specific to the eight major western U.S. river basins listed in Section 9503 of the SECURE Water Act, including detailed plots, data, and routed hydrology locations, is included in Reclamation, 2016 (Projections).

Temperature

U.S. average temperature has increased by 1.3 degrees Fahrenheit (°F) to 1.9°F since record keeping began in 1895; most of this increase has occurred since about 1970 (Melillo et al., 2014). The Western U.S. has warmed roughly 2 °F in the basins considered here and is projected to warm further during the 21st century. In many river basins, a warming trend has been noted since at least the 1970s (e.g., lower Colorado River basin) if not since the beginning of the 20^{th} century (e.g., Columbia River Basin, Sacramento and San Joaquin River basins, the Rio Grande basin, and most of the Missouri River basin). This rise in

[2] The 2011 SECURE Water Act Report to Congress developed a similar assessment using hydrologic projections featured in the IPCC Fourth Assessment (IPCC, 2007) and developed as part of the WCRP Project phase 3: http://www.usbr.gov/watersmart/docs/west-wide-climate-risk-assessments.pdf. The assessment described in this chapter updates that 2011 assessment.

temperature will continue trends already observed. Central estimates of this continued warming vary from roughly 5 to 7 °F depending on location. A summary of the projected temperature trends by Reclamation river basin are presented in Figure 1–1.

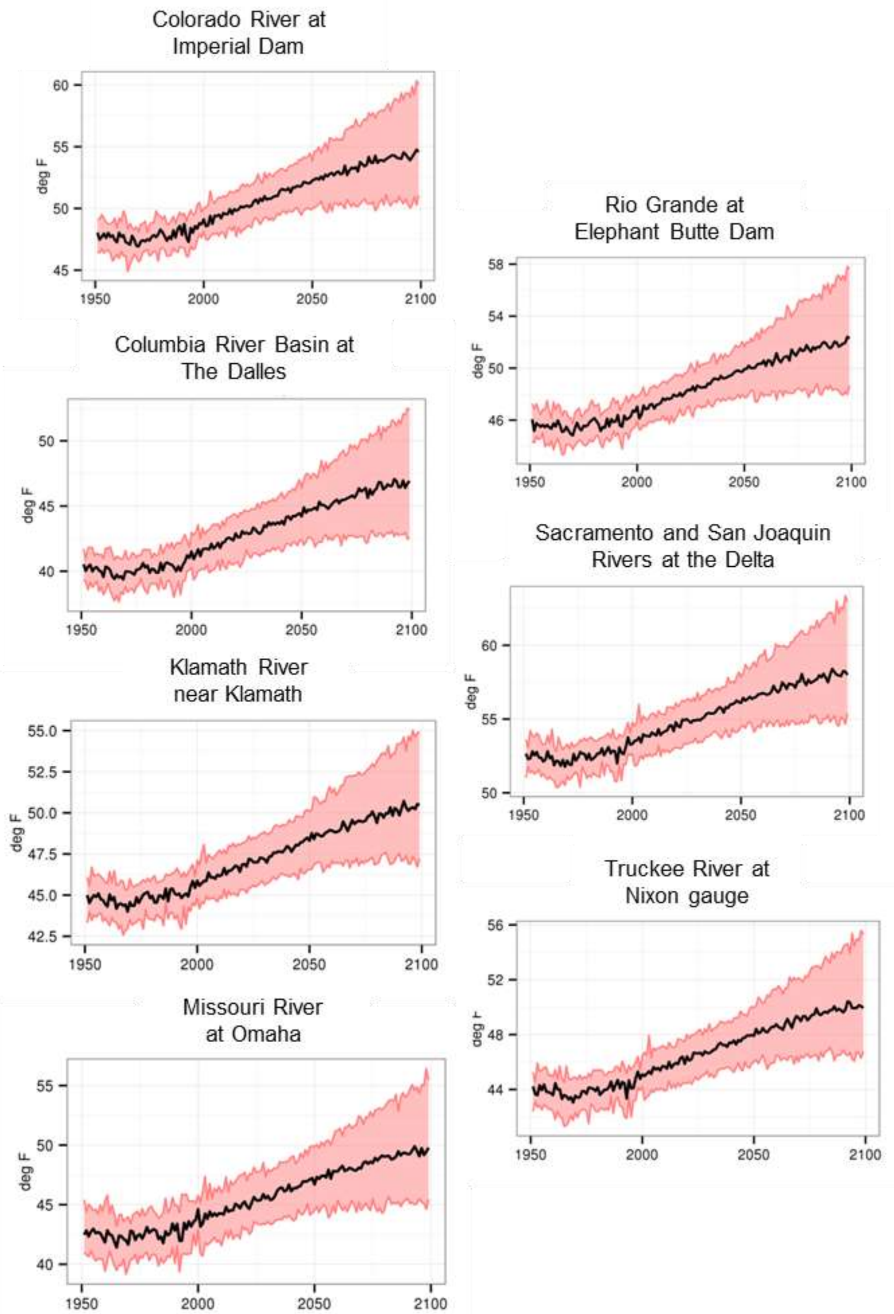

Figure 2–1. Projections of annual mean temperature in the major western river basins. Source: Reclamation, 2016 (Projections).

Annual mean temperature is plotted in degrees Fahrenheit. The heavy black line is the annual time series median value (i.e., ensemble-median). The shaded area is the annual time series of 10th to 90th percentiles. Note the plot scales vary by basin, but temperatures are expected to increase in all basins by approximately 5–7 °F by the end of the century.

Precipitation

Compared to projected changes in temperature, projected changes in precipitation are much less consistent among various climate models and are characterized by greater uncertainty. While projected changes in average total annual precipitation are generally small in many areas, both wet and dry extremes (heavy precipitation events and length of dry spells) are expected to increase substantially throughout the West (Georgakakos et al., 2014). Projected annual precipitation trends by river basin are presented in Figure 2–2.

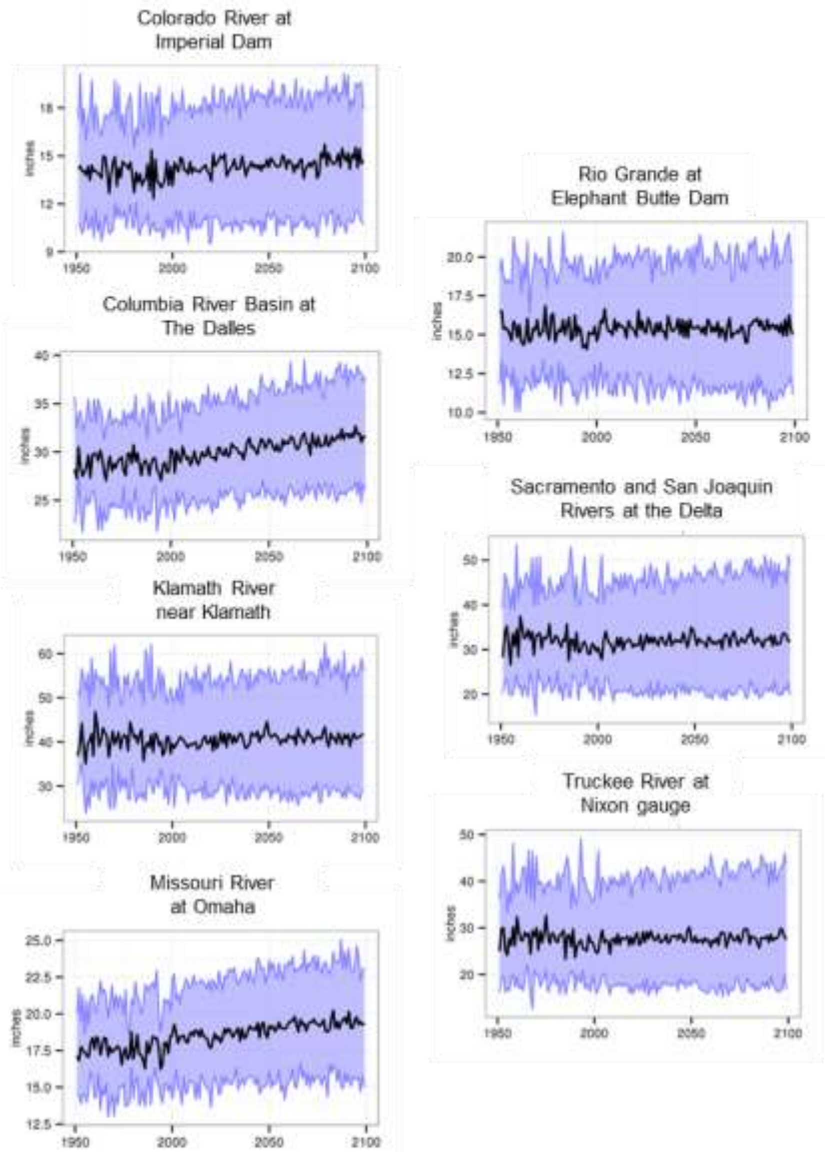

Figure 2–2. Projections of annual total precipitation in the major western river basins. Source: Reclamation, 2016 (Projections).

Total annual precipitation is plotted in inches. The heavy black line is the annual time series median value (i.e., ensemble-median). The shaded area is the annual time series of 10th to 90th percentiles. Note the plot scales vary by basin. Overall precipitation is projected to remain variable with no discernable trends in most basins.

Snowpack

Across most of the West, a trend toward more precipitation falling as rain and less as snow is already apparent. This is being observed both topographically (lower elevations receiving less precipitation in the form of snow) and seasonally (a shortening of the snow accumulation period). In most areas, projections of future hydrology suggest that warming and associated loss of snowpack will persist over much of the Western U.S. A summary of the projected annual snowpack trends are presented in Figure 2–3.

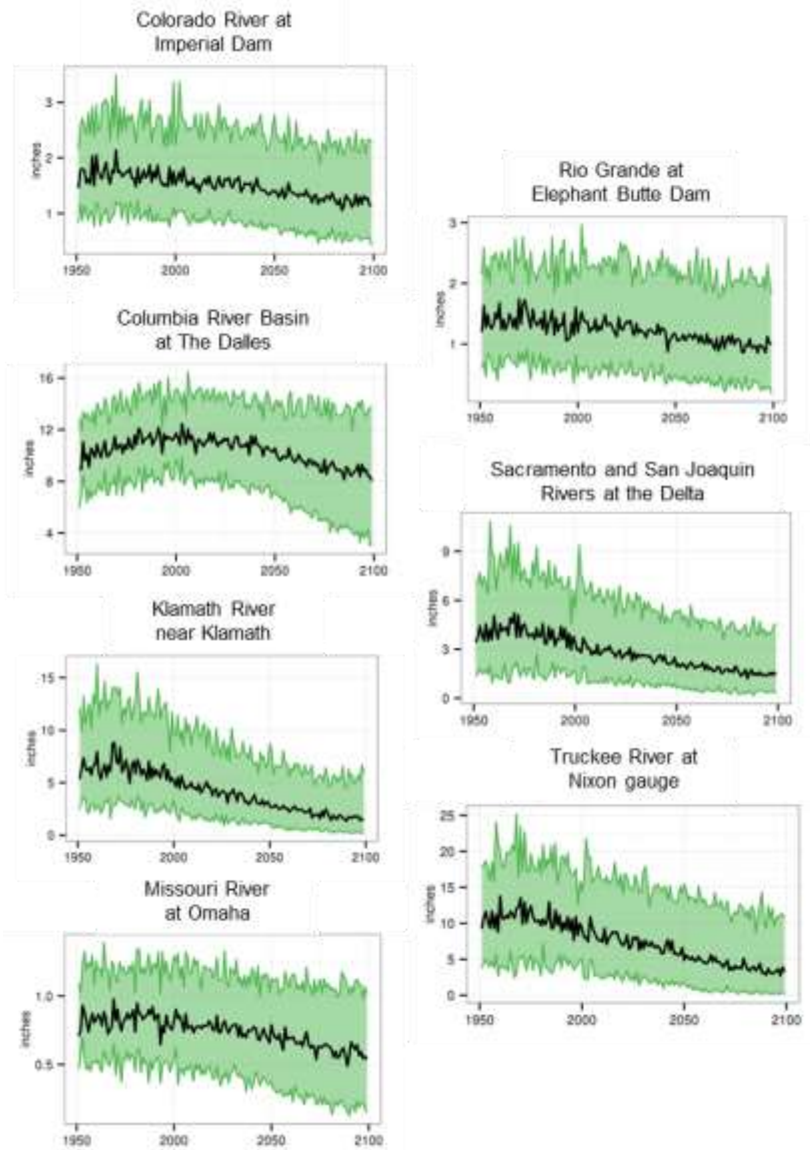

Figure 2–3. Projections of April 1st Snow Water Equivalent in the major western river basins. Source: Reclamation, 2016 (Projections).

Snow water equivalent is plotted in inches. The heavy black line is the annual time series median value (i.e., ensemble-median). The shaded area is the annual time series of 10th to 90th percentiles. Note the plot scales vary by basin. Trends toward decreasing snowpack are projected to continue across most of the West through the 21st century.

Runoff

Projected changes in temperature, precipitation, and snowpack are expected to change the magnitude and seasonality of runoff. Warming is expected to result in more rainfall-runoff during the cool season rather than snowpack accumulation, leading to increases in December–March runoff and decreases in April–July runoff. The southwest to the Southern Rockies is expected to experience gradual runoff declines during the 21st century. The Northwest to north-central U.S. is expected to experience little change through mid-21st century, with increases projected for the late-21st century. Projected annual runoff trends are presented in Figures 2–4 and 2–5, and are also summarized by river basin below.

- **Colorado River Basin:** Warmer conditions are projected to transition snowfall to rainfall, producing more December–March runoff and less April–July runoff. The median shift in the date of peak runoff is expected to be 12 days earlier by the end of the century.
- **Columbia River Basin:** Mean annual runoff is projected to increase by 2.9% by the 2050s. Moisture falling as rain instead of snow at lower elevations will increase the wintertime runoff with decreased runoff during the summer.
- **Klamath River Basin:** By the 2050s, projected warming is expected to change runoff timing, with a 23% increase in rainfall-runoff during the winter (December through March) and a 33% decrease in runoff during the spring and summer (April through July).
- **Missouri River Basin:** Mean annual basin runoff is projected to increase as much as 15%, with higher variability in sub-basin runoff by mid-century. Moisture falling as rain instead of snow at lower elevations is expected to result in an increase of the wintertime runoff and a decrease in summer runoff.
- **Rio Grande Basin:** Mean annual runoff is projected to decrease by 3% by the 2050s, with higher variability in sub-basins. By mid-century, warmer conditions are projected to transition snowfall to rainfall, shifting the timing of runoff by up to 11 days in the upper basin tributaries.
- **Sacramento and San Joaquin River Basins:** Mean annual runoff is projected to increase as much as 5.4% in the Sacramento and San Joaquin Rivers Delta by the 2050s. Moisture falling as rain instead of snow at lower elevations will increase wintertime runoff by 22% (December through March) and decrease springtime runoff by 27% (April through July).
- **Truckee River Basin:** Mean annual runoff is projected to increase by from 5.7% by the 2050s. Warmer conditions are projected to transition wintertime snow into rain, increasing December–March runoff and decreasing April–July runoff. The median date of peak runoff is expected to be 19 days earlier by the end of the century.

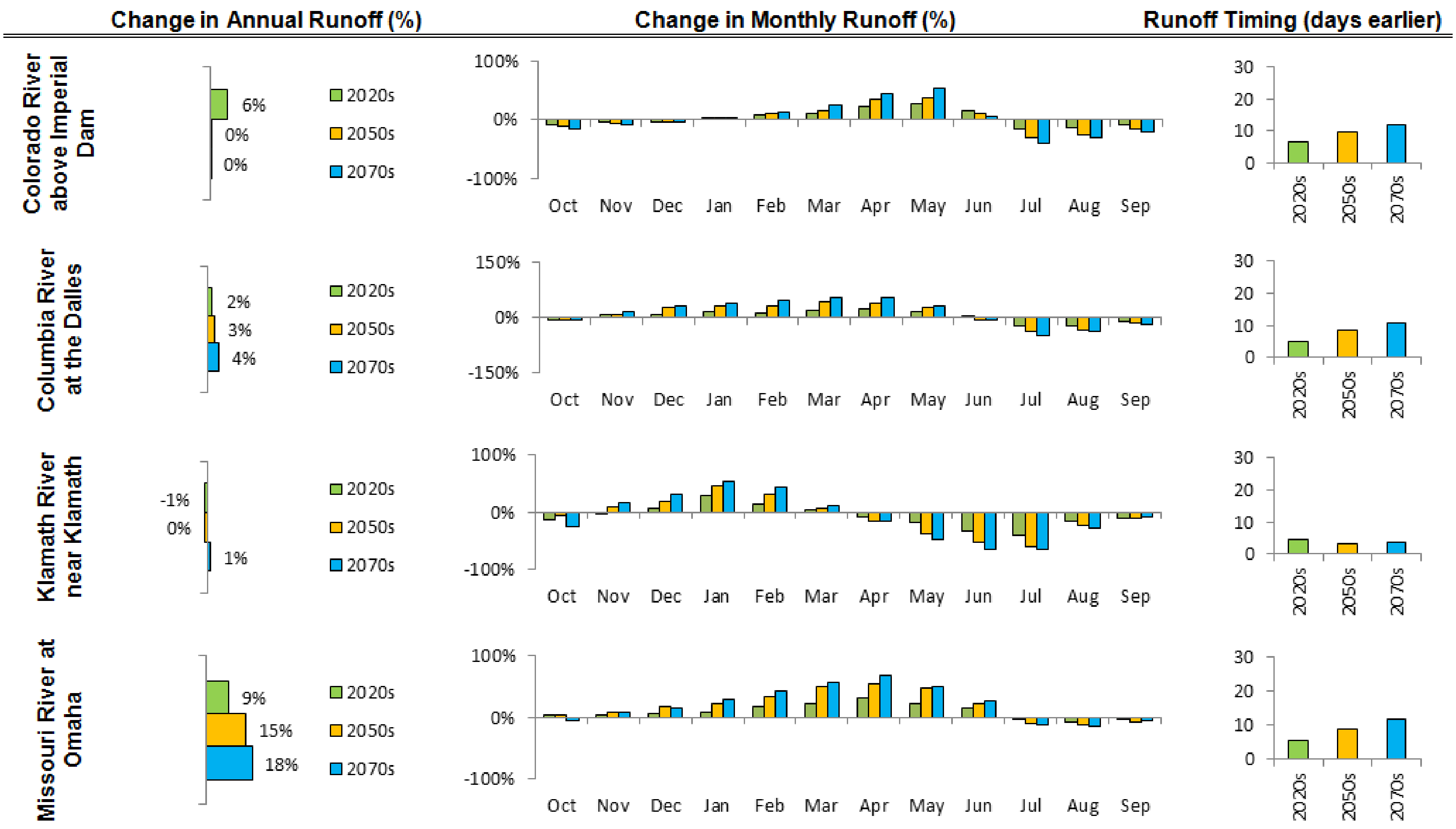

Figure 2–4. Projected shift in annual runoff, monthly runoff, and peak runoff date relative to the 1990s for the 2020s, 2050s, and 2070s in the major Reclamation river basins.

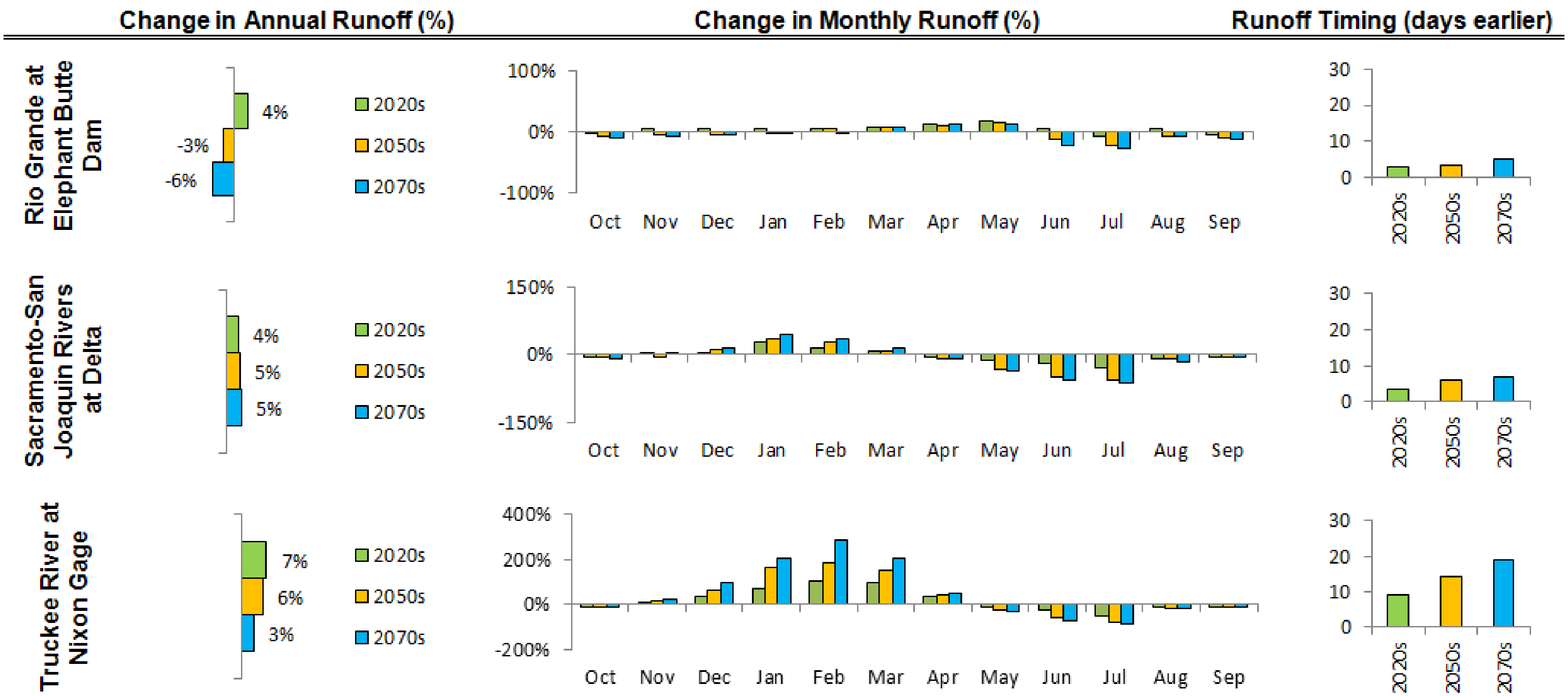

Figure 2–4 (continued). Projected shift in annual runoff, monthly runoff, and peak runoff date relative to the 1990s for the 2020s, 2050s, and 2070s in the major Reclamation river basins.

In almost all cases, projections indicate an increase in cool-season runoff (November through April), and a decrease in warm-season runoff (May through September) as well as a shift to earlier peak runoff timing in every basin.

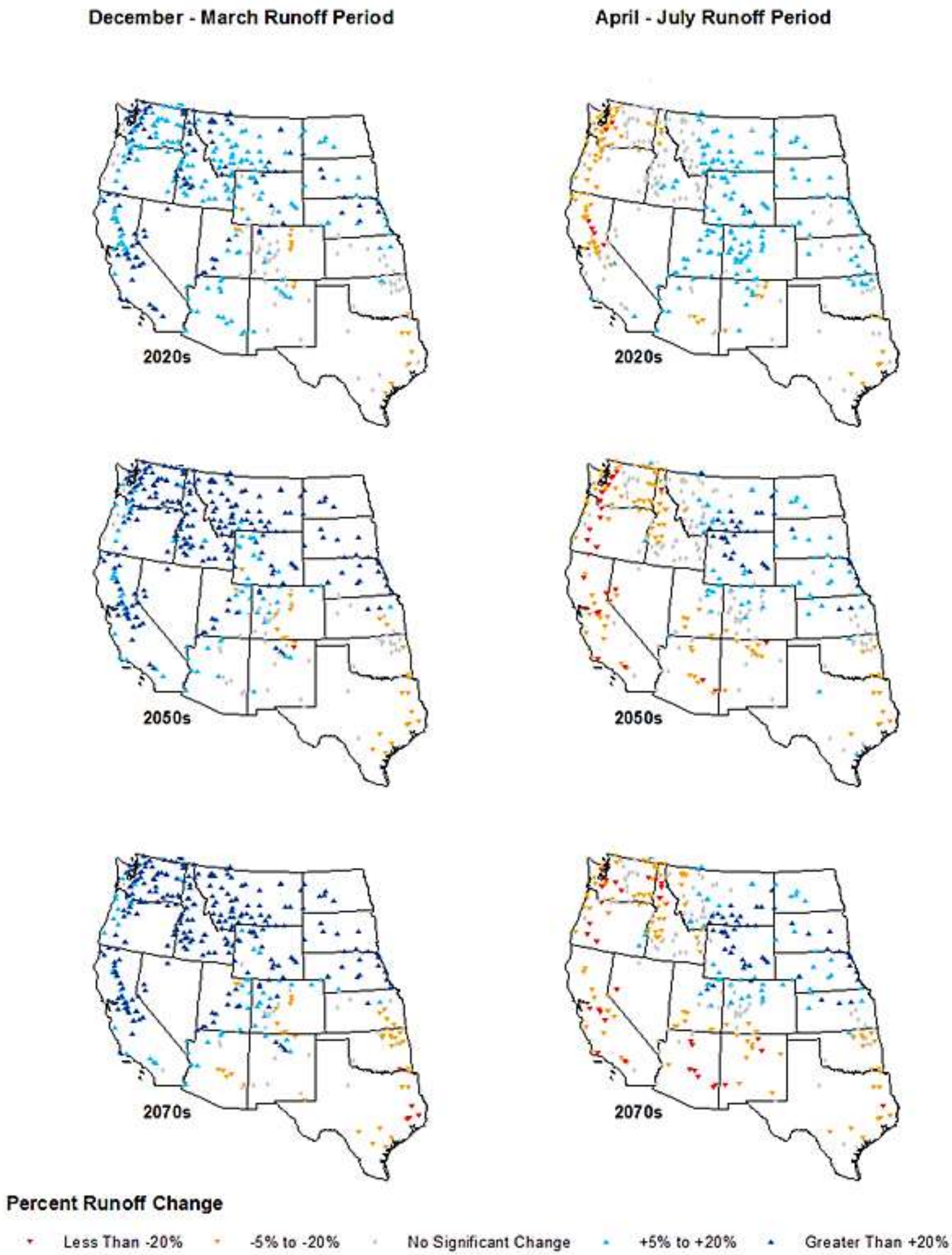

Figure 2–5. Projected change in December-March and April-July runoff relative to the 1990s for the 2020s, 2050s, and 2070s distributed over the West.

Moisture falling as rain instead of snow at lower elevations is projected to increase wintertime runoff and decrease runoff during the summer.

Inspection of the underlying ensemble of projection information shows that there is significant variability and uncertainty, particularly with respect to precipitation. Changes in the frequency and intensity of extreme events have significant implications for the management of floods, other high flows, and storable water. As already noted, studies indicate a strong potential for the occurrence of more intense precipitation events in most areas of the West. This in turn is expected to increase the frequency and/or magnitude of extreme runoff events. Evidence also suggests that we can anticipate more year-to-year variability of surface water supplies in at least some areas: for example, the future of the Southwest may include longer, more extreme dry (and wet) periods than previously observed (Georgakakos et al., 2014).

Where runoff is projected to increase relative to historical conditions, supplies available to meet delivery needs may increase (especially where adequate storage or other mechanisms exist for aligning the timing of water demands with runoff). Where runoff is projected to decrease, additional challenges for meeting water delivery needs can be anticipated. Impacts on water deliveries will vary from basin to basin and from year to year, depending on the timing and magnitude of water inflows and demands, available storage, and water delivery options.

Summary

In summary, temperature increases are projected to continue, resulting in decreased snowpack, differences in the timing and volume of spring runoff, and an increase in peak flows for some Western U.S. basins. The impacts to snowpack and runoff affect the timing and availability of water supplies. Precipitation changes are also expected to occur, interacting with warming to cause longer term and more frequent droughts and larger and more numerous floods, varying by basin. Note that these summary statements draw attention to mean projected changes in temperature and precipitation, characterized generally across the Western U.S.

- Temperature increases have resulted in decreased snowpack, differences in the timing and volume of spring runoff, and an increase in peak flows for some Western U.S. basins. The impacts to snowpack and runoff affect the timing and availability of water supplies.
- Warming is expected to continue, causing further impacts on supplies, increasing agricultural water demands, and affecting the seasonal demand for hydropower electricity.
- Precipitation changes are also expected to occur, interacting with warming to cause longer term and more frequent droughts and larger and more numerous floods, varying by basin.
- Cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central U.S., but little change to slight decreases are projected over the Southwestern U.S. to Southern Rockies.

- Warm season runoff is projected to decrease substantially over a region spanning southern Oregon, the Southwestern U.S., and Southern Rockies. However, north of this region warm season runoff is projected to change little or to slightly increase.
- Projected increasing precipitation in the northern tier of the Western U.S. could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western U.S. could amplify warming-related decreases in warm season runoff

Collectively, the impacts of climate change to water resources give rise to difficult questions about how best to operate Reclamation facilities to address growing demands for water and hydropower now and how to upgrade and maintain infrastructure to optimize operations in the future. More extreme variations in climate will make it difficult for Reclamation to meet competing demands for water. Warming is expected to continue, causing further impacts on supplies, increasing agricultural water demands, and affecting the seasonal demand for hydropower electricity. Increased intensity of droughts and floods also raises concerns about infrastructure safety, the resiliency of species and ecosystems to these changes, and the ability to maintain adequate levels of hydropower production. Chapters 3 through 10 translate the simulated hydrologic effects under projected climate change into geographic impacts on water resources including water deliveries, flood management, hydropower generation, recreation, ecosystem resiliency, and water quality.

2.2 Uncertainty

The WWCRA hydroclimate projections were designed to take advantage of best available datasets and modeling tools; follow methodologies documented in peer reviewed literature, and update the consistent west-wide data developed for the 2011 SECURE Water Act Report to Congress. It should be noted that there are a number of analytical uncertainties, including uncertainties associated with climate projection information and assessing hydrologic impacts. Uncertainty in both climate projection information and assessing hydrologic impacts is discussed in detail in the WWCRA: Hydro-Climate Projections Technical Memorandum.[3]

The 2011 SECURE Water Act Report to Congress developed a similar assessment using bias corrected and spatially downscaled (BCSD) hydrologic projections using CMIP3 projections. This chapter's assessment updates the 2011 assessment using CMIP5 projections. A comparison of projected temperature and precipitation for both the BCSD-CMIP3 and BCSD-CMIP 5 projections is provided in Figure 2–6.

[3] The West-Wide Climate Risk Assessments: Hydroclimate Projections Technical Memorandum referenced in this section is available on the Reclamation website here: http://www.usbr.gov/watersmart/docs/west-wide-climate-risk-assessments.pdf

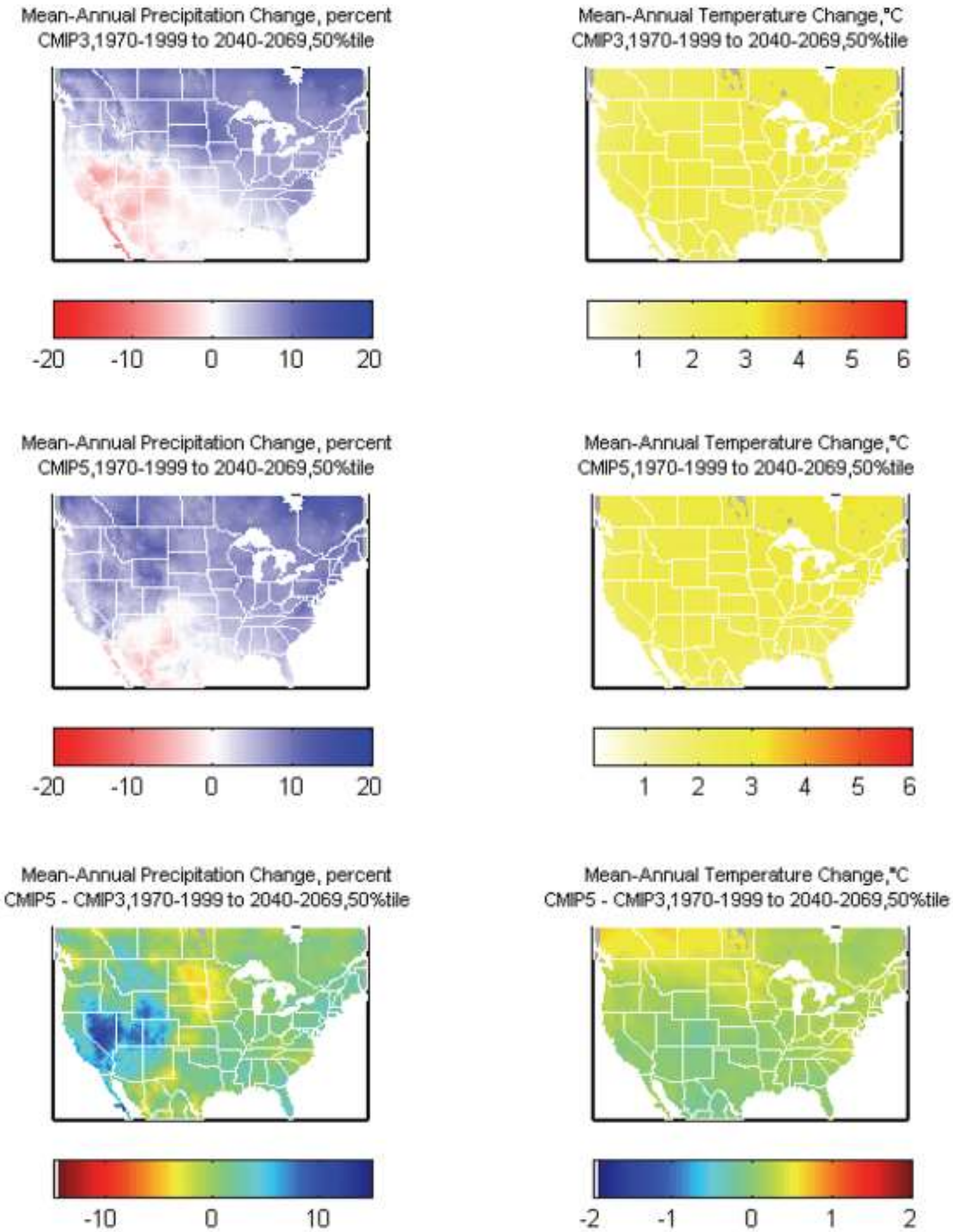

Figure 2–6. Central tendency changes in mean annual precipitation and temperature over the contiguous U.S. from 1970-1999 to 2040-2069 for BCSD-CMIP3 (top row), BCSD-CMIP5 (middle row), and the difference (bottom row). Source: Reclamation, 2013.

The CMIP5 projections indicate a similar pattern for temperature and precipitation with CMIP5 projections indicating greater warming in the north and a slight shift of increasing precipitation into the Upper Colorado River Basin and Northern California.

The BCSD-CMIP5 hydrology shows hydroclimate changes (i.e., temperature, precipitation, and runoff) that are generally similar to BCSD-CMIP3 across the contiguous U.S. However in the BCSD-CMIP5 hydrology, there are some region-specific differences including greater warming to the North, regions of more increased precipitation change in the West and Great Plains (although varying by season), and differences in runoff change that more closely follow those found for precipitation than for temperature (Reclamation, 2013 [CMIP]).

3 West-wide Water Demands Assessment

Climate change will alter not only water supply, but also demands for water. Below is a summary of projected changes in demands for water for municipal and industrial use, for irrigation, and due to reservoir evaporation.

3.1 Municipal & Industrial (M&I) Use

In recent decades, many of the Nation's fastest-growing municipal areas have been in the arid and semi-arid West (e.g., Las Vegas, southern California, Colorado's Front Range, Utah's Wasatch Front, southern Arizona). Substantial population growth in these and other urban areas of the West is anticipated to continue into the foreseeable future (e.g., Pincetl et al., 2013).

Outdoor use of water for maintaining vegetation at private lots, public parks, and other urban landscapes is generally expected to experience a gradual increase in evaporative demand along with rising temperatures during the 21st century, similar to irrigated agricultural vegetation. Except where these increased evaporative demands are offset by a corresponding increase in precipitation, or by measures to reduce outdoor use, M&I consumptive water demands also are expected to increase.

Notably, outdoor water use represents more than half of residential water use in many urbanized areas of the arid West (Mayer et al., 1999), and as much as 90% of household consumptive use. Thus, outdoor watering practices, and potential changes in those practices, represent (along with changes in urban population) factors with the greatest potential to influence M&I consumptive demands.

3.2 Irrigation Demands

As previously mentioned, the WWCRAs provide important baseline projections of risks to water supplies, changes in water demand, and potential operational impacts. Risks to future water demands were quantified in a west-wide assessment entitled West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections Technical Memorandum (Reclamation, 2015 [Irrigation])[4]. This assessment identified potential changes in crop irrigation demand in the eight major western river basins listed in the SECURE Water Act. Agricultural demand for water is highly susceptible to climate change.

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[4] The West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections Technical Memorandum referenced in this section is available on the Reclamation website here: http://www.usbr.gov/watersmart/wcra/docs/irrigationdemand/WWCRAdemands.pdf

Impacts across the evaluated basins vary, but according to the 2015 analysis, evapotranspiration (ET)—evaporation and plant transpiration—is projected to increase in all Western basins due to increasing temperatures, including an increase in the annual ET for perennial agricultural crops and many annual crops. Various assumptions are incorporated into any agricultural demand projection, in addition to the uncertainties inherent in the underlying climate and hydrological outlooks. As summarized in Table 2–1, some factors are projected to increase agricultural demands, while others would reduce demands. Other factors, such as agricultural management practices, have effects that are difficult to forecast.

Table 2–1. Factors, Including Changes in Climate and Atmospheric Conditions, Potentially Affecting Future Agricultural Water Demands

Factors Increasing Demand	Factors Reducing Demand	Factors With Unknown Effects
Increased evaporation and evapotranspiration due to temperature increase.	Reduced losses of agricultural water through improvements to delivery practices and facilities.	Changes in the types and characteristics of crops grown.
Increased evapotranspiration due to extended growing seasons.	Less per-unit crop water use associated with increased atmospheric CO_2 and ozone.	Changes in agricultural management practices (e.g., more dry-year fallowing or deficit-irrigation cropping).
Increase in lands requiring supplemental irrigation to remain viable.	Increased crop failure due to increased pests, diseases, etc.	Transfers of water between different uses.
Increase in irrigated lands due to northward warming.	Conversion of irrigated cropland to other less water-intensive uses.	Effects on the surface energy balance from factors other than temperature.
Increased livestock water demands.		
Increased total crop yield associated with increased atmospheric CO_2.		

3.3 Reservoir Evaporation

The WWCRA demands assessment also includes projections of evaporation for 12 reservoirs within the eight major Reclamation river basins (see Figure 2–7). The reservoirs at which evaporation was estimated include: Lake Powell (Colorado River), Lake Mead (Colorado River), American Falls (Columbia, Snake River tributary), Grand Coulee (Columbia), Upper Klamath Lake (Klamath River), Canyon Ferry Lake (Missouri River), Boysen Reservoir (Missouri River), Elephant Butte Reservoir (Rio Grande) , Lake Shasta (Sacramento River), Millerton Lake (San Joaquin River), Lake Tahoe (Truckee River), and Lahontan Reservoir (Carson River).

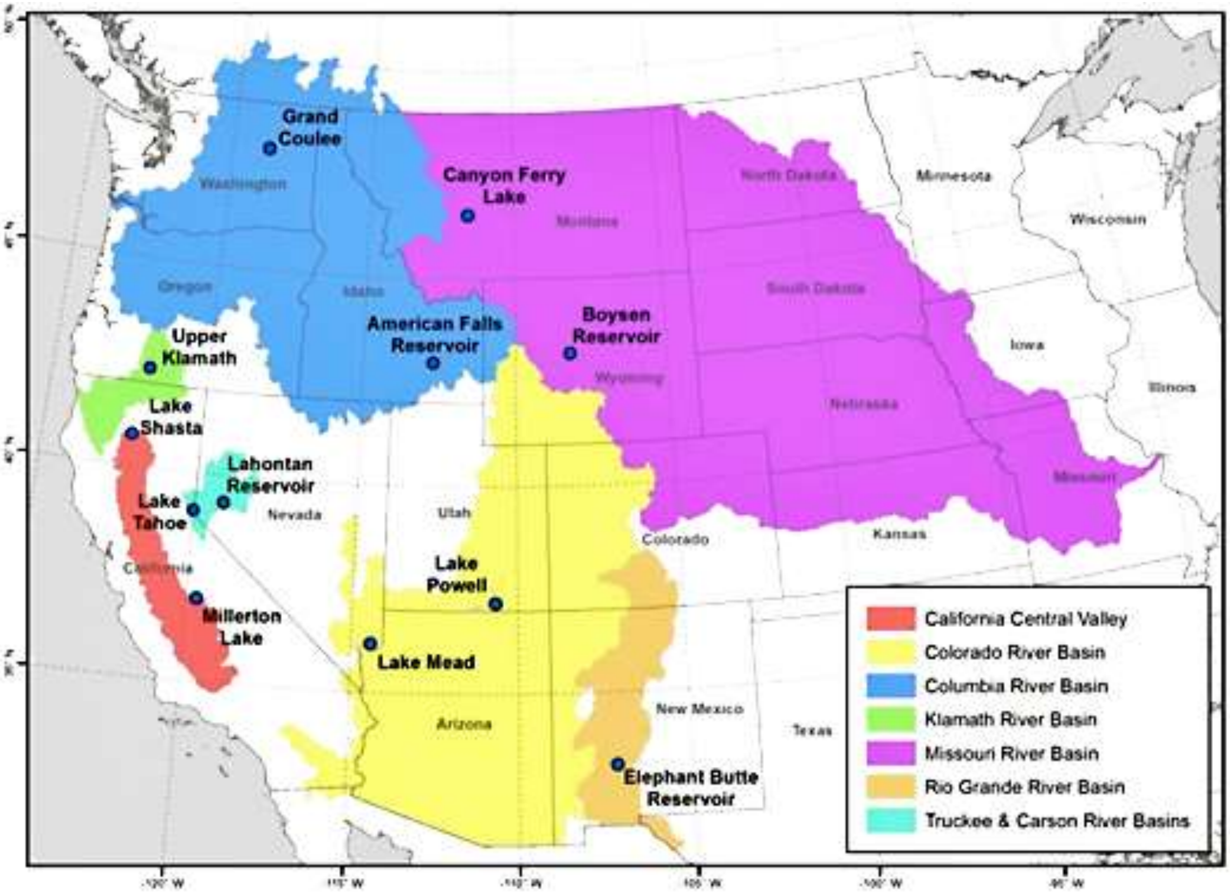

Figure 2–7. Reservoirs and lakes where an evaporation projection model was applied. West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections (Reclamation 2015b).

Open water evaporation from lakes and reservoirs is an important water budget component to consider for water planning, modeling of hydrologic systems, and projections of future water demands and supply. Evaporation pans are typically used to estimate lake and reservoir evaporation; however, the timing and magnitude of pan evaporation is not necessarily representative of actual evaporation from a lake or reservoir for numerous reasons, including significant time lags between peak pan evaporation and peak reservoir evaporation during a year, and has been shown to be highly uncertain (Hounam, 1973 and Morton, 1979). Open water evaporation in this study was estimated using an energy balance model, which has been widely applied for estimating operational reservoir and lake evaporation with limited climatic and heat storage information. Key results for this study include:

- The ensemble median of annual reservoir evaporation and net evaporation (evaporation minus precipitation) is projected to increase in all basins. As an example, projections for the Colorado River Basin (Lake Powell) are provided in Figure 2–8.

- Projected annual evaporation increases are typically around 2 to 6 inches by 2080 at most reservoirs modeled.
- However, the increase in annual net evaporation is relatively small at some reservoirs due to increased precipitation and nearly equal to or slightly greater than historical evaporation at others due to decreased precipitation.

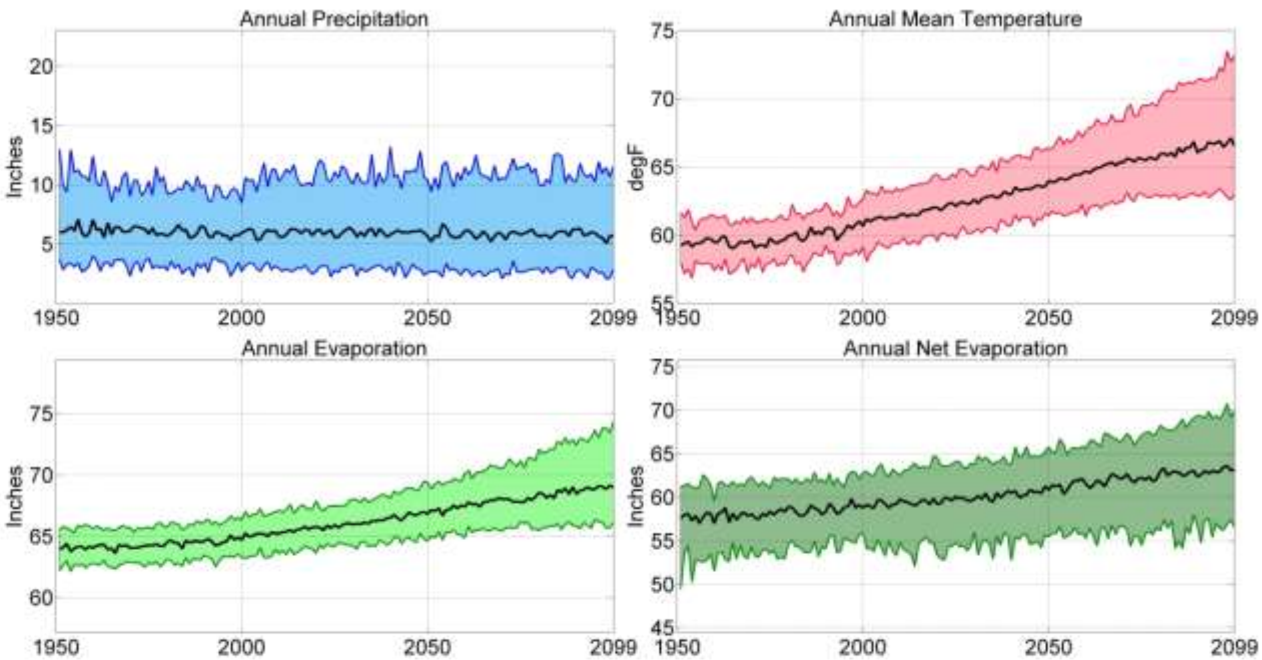

Figure 2–8. Example of projections for the Colorado River Basin – Lake Powell ensemble median and 5th and 95th percentile annual precipitation, temperature, reservoir evaporation, and net evaporation.

The heavy black line is the annual time series of 50 percentile values (i.e., ensemble-median). The shaded area is the annual time series of 5th to 95th percentiles. Plots for each major river basin exhibiting varying degrees of increasing evapotranspiration and reservoir evaporation due to warming are included in the Technical Memorandum (Reclamation, 2015 [Irrigation]).

3.4 Uncertainty

The West-Wide Climate Risk Assessment: Irrigation Demand and Reservoir Evaporation Projections Technical Memorandum (Reclamation, 2016 [Projections]) summarizes potential future climate impacts on irrigation demand and reservoir evaporation across the Western U.S. using best available datasets and methodologies. Uncertainties in projections of water demands are associated with the climate projections and the methods used for assessing irrigation demand and reservoir evaporation. It is important to note that these projections do not represent a comprehensive demand assessment, but are part of a focused examination of primary climate impacts on plant water needs and reservoir evaporation. Beyond climate related considerations, a number of additional factors may influence irrigation demands in the future, such as changing cropping patterns driven by market prices, changes in irrigation practices and soil-evaporation components, changes in crop varieties and phenologies, and total acres kept in production. A comprehensive future irrigation demand assessment would require consideration of all factors and strong stakeholder involvement. Uncertainty is discussed in more detail in Reclamation 2015 (Irrigation).

4 Groundwater Recharge and Discharge

Changes in temperature and precipitation will affect Western hydrology in multiple ways, including impacts to snow hydrology, surface water, and groundwater. Among the most significant of these anticipated effects are changes in snowpack accumulation and melt, changes in runoff timing and quantity, and additional risks associated with extreme runoff events. Groundwater and surface water are closely linked. Impacts to one will affect the other, directly or indirectly, over a shorter or longer timeframe, and through a variety of possible pathways.

When evaluating the potential effects of climate change on Western water resources, groundwater is an important consideration, as it comprises an estimated 33% of total freshwater diversions and withdrawals used for human purposes in the 17 western states (Maupin et al., 2014). The decreased snowpack could result in decreased groundwater infiltration, runoff and ultimately lower base flows in the rivers during the summer. Typically, groundwater is interconnected with surface water and withdrawals of groundwater will affect downstream flow in much the same way as withdrawals from the river itself. At the other extreme, geologic conditions and distances may result in weak, non-existent, or highly lagged interactions between groundwater and surface water, and recharge to associated aquifers may take millennia.

Thus, the pathways and rates of recharge versus withdrawal are fundamental considerations for sustaining groundwater resources. The rate of groundwater withdrawal, often exacerbated by drought, currently outstrips recharge in some areas of the West, including much of California's Central Valley (Harter and Dahlke, 2014) and certain areas of the Great Plains dependent on the Ogallala Aquifer (Konikow, 2013). Long-term sustainability of groundwater supplies is possible only where withdrawals are offset with —a balance that can be particularly challenging during severe or prolonged droughts.

With increases in the variability and uncertainty of precipitation and surface water supplies, it is anticipated that many Western communities will become more reliant on groundwater as a supplemental or primary water supply source for agricultural and municipal purposes. Recharge to groundwater also is expected to be affected by shifts in precipitation patterns, increased temperature, and other factors affecting plant uptake and evapotranspiration, just as these shifts will impact surface water.

4.1 U.S. Geological Survey Coordination

Through the WWCRAs, Reclamation coordinates with the USGS in several ways to assess groundwater availability and to assess the impact of climate change on groundwater recharge and discharge. As part of WaterSMART, the USGS has implemented a National Water Census (NWC). In response to the SECURE Water Act, the USGS has implemented a new program: the Water Availability and Use Science Program (WAUSP).

Regional Groundwater Assessments: Through the WAUSP, the USGS is undertaking a series of regional groundwater availability studies in the West to improve our understanding of groundwater availability in major aquifers across the Nation. These studies provide valuable data and tools that are leveraged in Reclamation's Basin Studies to assess climate impacts and adaptation strategies. A map of the locations is provided in Figure 2–9.

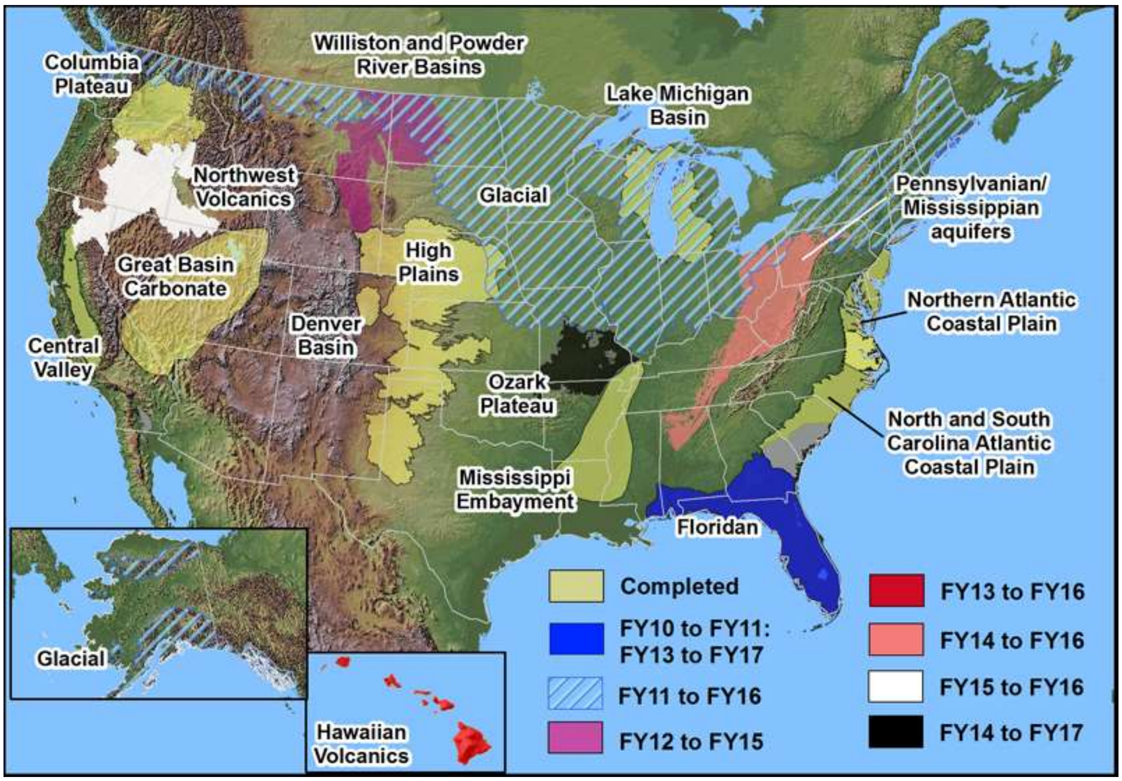

Figure 2–9. Map of USGS Groundwater Resources Program regional scale groundwater study areas, with the schedule for the studies indicated. (Courtesy of USGS. Updated April 2015).

Highlights from the regional groundwater studies relevant to western river basins are provided below:

- The **Pacific Northwest Volcanic Aquifer Study** will quantify groundwater resources and geothermal energy potential in much of eastern Oregon, northeastern California, southwestern Idaho, and northernmost Nevada. Groundwater is the major source of year-round dependable water supply in the study area, and water is a necessary component of geothermal energy development.

- The **Williston and Powder River Basins Study** will (1) quantify current groundwater resources in this aquifer system, (2) evaluate how these resources have changed over time, and (3) provide tools to better understand system response to future anthropogenic demands and environmental stress. The development of two nationally important energy-producing areas, the Williston structural basin (containing the Bakken Formation) and Powder River structural basin provide an important opportunity to study the water-energy nexus within a groundwater context. Large amounts of water are needed for energy development in these basins.
- The **High Plains Aquifer Study** quantified current groundwater resources, evaluated changes in those resources over time, and provided tools to forecast how those resources respond to stresses from future human and environmental uses. The improved quantitative understanding of the basin's water balance provided by this USGS study not only provides key information about water quantity but also is a fundamental basis for many analyses of water quality and ecosystem health.
- The **Columbia Plateau Regional Aquifer System Study** covers over 50,000 square miles of eastern Oregon and Washington and western Idaho. The USGS conducted a study of the Columbia Plateau Regional Aquifer System to characterize the hydrologic status of the system, identify trends in groundwater storage and use, and quantify groundwater availability.
- The **Great Basin Carbonate and Alluvial Aquifer Study** quantified current groundwater resources, evaluated how those resources have changed over time, and developed tools to assess system responses to stresses from future human uses and climate variability.
- The **Central Valley Aquifer Study** includes an assessment of groundwater availability and quantification of groundwater resources using a variety of tools. The ultimate benefit of this assessment will be a better understanding of how the system responds to current and future human and environmental stresses that will prove useful to water managers in their decision making process related to this valuable resource.
- The **Denver Basin Aquifer Study** addressed an important and non-renewable source of water for municipal, industrial, and domestic uses in the Denver and Colorado Springs metropolitan areas. The USGS conducted a groundwater availability of the Denver Groundwater Basin to enhance our understanding of regional groundwater flow and aquifer storage, to evaluate current conditions, and to predict future conditions.
- The **Middle Rio Grande Basin Study** was a 6-year effort (1995-2001) to improve the understanding of the hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin in order to provide the scientific information needed for water-resources management. This initial proof of concept study was conducted prior to the development of the strategy outlined in Circular 1323 and served as a precursor to current

Groundwater Resources Program (GWRP) regional groundwater availability studies.

National Brackish Groundwater Assessment: The use of brackish groundwater to supplement or, in some places, replace the use of freshwater sources has been analyzed as a potential climate resilient adaptation strategy in a number of WaterSMART Basin Studies. The WWCRA Implementation Team is coordinating with the USGS to gain a better understanding of the location and character of brackish groundwater in the Western U.S. An assessment is needed to expand development of the resource and provide a scientific basis for making policy decisions. To address this need, the USGS is conducting an assessment of brackish aquifers, using a consistent national approach, to compile existing information that can be used to:

- Characterize brackish aquifers
- Describe dissolved-solids concentrations, including other chemical characteristics, using existing data
- Describe the horizontal and vertical extents of aquifers containing brackish groundwater
- Describe ability of aquifers to yield water
- Identify current brackish groundwater use
- Generate national maps of dissolved-solid concentrations
- Identify data gaps that limit full characterization of brackish aquifers

5 Climate Coordination and Research

Reclamation is actively engaged in multiple collaborative efforts with Federal and non-Federal partners to develop and share information for a common understanding of climate change impacts to water resources in the West. This section highlights west-wide collaboration to develop climate and hydrology information for use by Reclamation. Additional information on coordination activities specific to each western river basin, including the strategies developed to address potential water shortages, is included in Chapters 3 through 10.

5.1 Reclamation's Science and Technology Program Research and Development

Fundamental to developing new information for adapting to climate change is assessing the current state of knowledge, identifying where gaps exist, and finding opportunities to address those gaps. Reclamation's Science and Technology Program is taking a leading role to develop the data and tools necessary to support climate change adaptation within Reclamation and by stakeholders.[5] Key highlights for the Science and Technology Program include the following:

- **Downscaled Climate and Hydrology Projections Web Service:**[6] Since 2007, Reclamation has led a partnership of nine Federal, academic, and non-governmental organizations to provide future projections of temperature, precipitation, hydrology, and streamflow throughout the continental U.S. to support locally relevant decision making. These information resources are served through a website that provides users access to the monthly gridded precipitation, temperature and hydrologic projection data, as well as additional climate projection information that covers the contiguous U.S. Reclamation and collaborators have also partnered with other information hosts to provide mirror access at other website, including the U.S. General Services Administration's Data.gov, [7] USGS's Geo Data Portal,[8] and the Federal Geospatial Data Committee's GeoPlatform.gov.[9] Reclamation also leveraged this web service in 2010-2011 to produce a Streamflow Projections Website that accompanied the release of the 2011 SECURE Water Act Report focusing on the streamflow reporting locations of that report.[10]

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5 Downscaled Climate and Hydrology Projections Web Service: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

6 For detailed information on Reclamation's Science and Technology Program's Climate Change Research visit the Reclamation website: http://www.usbr.gov/research/climate

7 U.S. General Services Administration's Data.gov: http://www.data.gov/climate

8 U.S. Geological Survey's Geo Data Portal: http://cida.usgs.gov/gdp

9 Federal Geospatial Data Committee's GeoPlatform.gov: https://www.geoplatform.gov

10 Streamflow Projections Website: http://www.usbr.gov/WaterSMART/wcra/flowdata/index.html

- **Third Edition of the Literature Synthesis on Climate Change Implications for Water and Environmental Resources:** This report supports long-term water resources planning with region-specific climate change information, summarizing recent literature on the current and projected effects of climate change on hydrology and water resources. This report, which contains information surveyed through 2012, was assembled by Reclamation and was subjected to external review by staff from each of the five National Oceanic and Atmospheric Administration Regional Integrated Sciences and Assessments centers in the Western U.S.
- **Climate and Hydrology Impacts Assessment Tools:** Since 2011, Reclamation's Science and Technology Program has partnered with the U.S. Army Corps of Engineers (USACE) and National Center for Atmospheric Research (NCAR) to improve tools and methods for assessing climate change impacts on water resources. An initial project has involved identifying strengths and weaknesses of current methods that inform Reclamation's vulnerability assessments and adaptation planning. The project focused on methods to downscale climate projections and simulate hydrologic impacts, including those that the WWCRA team has relied upon to assess vulnerabilities and support adaptation planning. This initial effort revealed opportunities for research to develop improved techniques, and has led to a subsequent effort to develop and apply such techniques.
- **Climate Extremes Assessment Tools:** Since 2011, Reclamation's Science and Technology Program has partnered with the University of Colorado’s Cooperative Institute for Research in Environmental Studies (CIRES) and NOAA’s Earth System Research Laboratory (ESRL) to improve tools and methods for assessing climate change impacts on extreme events. Initial projects occurring in 2012-2013 focused on more physically-based methods for estimating climate change impacts on storm-scale events happening during the warm season along the Colorado Front Range, and also on tools to better diagnose moisture origins and storm setup for heavy precipitation events across the Intermountain West. These efforts have led to successor projects where the focus is on developing tools that can be applied by Reclamation’s Technical Service Center as they estimate wet weather extremes and associated hydrologic hazards to support Dam Safety Office risk investigations in a changing climate.

5.2 Technical Assessments and Guidance

Reclamation’s Climate Change Adaptation Strategy recognizes that the presence of critical Federal facilities throughout the West and the national interest in addressing climate change necessitates a heightened role for Reclamation to continue to address water resource challenges by providing expert technical assistance and the best available science through collaborative planning efforts. The planning process relies upon access to information to make statements about future climate possibilities. This section highlights activities using the existing information on climate change impacts, identifying gaps in knowledge, and taking a step forward to use this information in decision processes through a science based approach.

Technical Guidance for Incorporating Climate Change Information into Water Resources Planning Studies: In 2014, Reclamation released Technical Guidance for Incorporating Climate Change Information into Water Resources Planning Studies (Reclamation, 2014 [Guidance]).[11] The objective of this guidance is to assist Reclamation study teams in navigating the range of technical methods available to account for climate change impacts in planning studies. This document is designed to be used in the existing decision-making processes to understand climate change impacts on water supply, demand, and criteria that govern or guide water management.

Selecting Climate Projection Information for Water Resources Studies, Environmental Analyses, and Planning Applications: This document provides clear and concise information regarding the available climate projection information resources and methods to select a subset of climate projections for detailed analysis in support of a specific study.[12] When considering and analyzing the potential impacts of climate change, planners and analysts must choose an appropriate source of climate projection information within the context of their specific study or analysis. The scientific community has developed a vast amount of information regarding projected future climate conditions. Selecting an appropriate source of climate projection information for use in a given study or analysis is a critical first step in considering and analyzing potential climate change impacts in support of water resources and environmental planning.

Reclamation has made significant progress in assessing the impacts of climate change to water resources and implementing on-the-ground actions to mitigate impacts. However, Reclamation's Climate Change and Adaptation Strategy recognizes that more needs to be done to use information about future climate change in order to make decisions now about how best to operate Reclamation reservoirs, prioritize investments in new or improved facilities, and protect species and habitat in a changing climate. Additional information specific to each western river basin, including the strategies developed to address potential water shortages, is included in Chapters 3 through 10.

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[11] The guidance is available on the WaterSMART website: http://www.usbr.gov/watersmart/wcra/docs/WWCRATechnicalGuidance.pdf.

[12] The guidance is available on the WaterSMART website: http://www.usbr.gov/watersmart/wcra

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