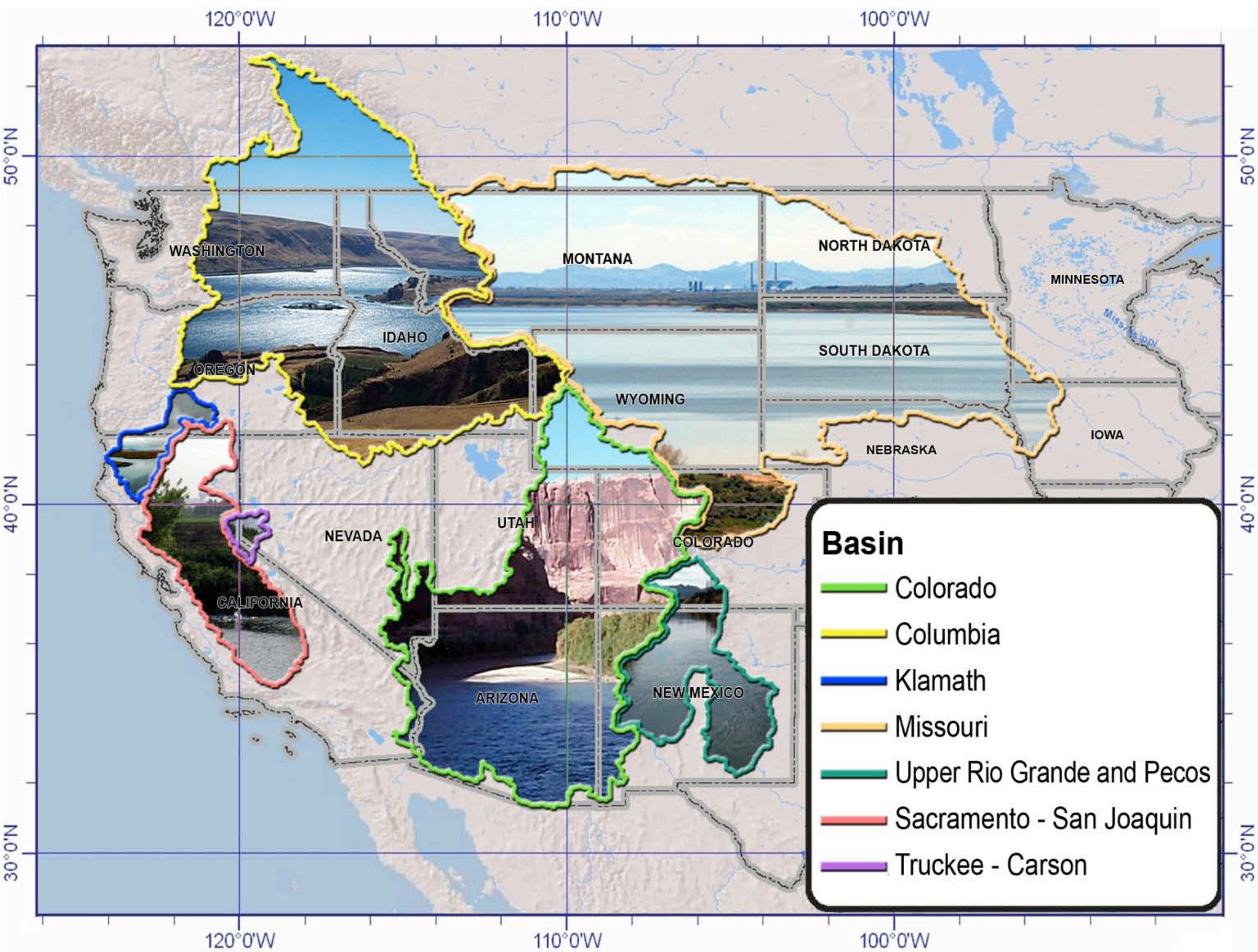
RECLAMATION
Managing Water in the West

SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011



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

April 2011

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) – Reclamation Climate Change and Water 2011

Prepared for:

United States Congress

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Bureau of Reclamation

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

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Executive Summary

Background

Established in 1902, the Bureau of Reclamation (Reclamation) is best known for the dams, powerplants, and canals it constructed within the 17 Western United States. Today, Reclamation is the largest wholesaler of water in the United States and the second largest producer of hydroelectric power in the Western United States. Reclamation's mission is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Reclamation's vision is to protect local economies and preserve natural resources and ecosystems through the effective use of water. This vision is achieved through Reclamation's leadership, use of technical expertise, efficient operations, and responsive customer service.

In meeting its mission, Reclamation's planning and operations rely upon assumptions of present and future water supplies based on climate. 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 determining what wet, dry, and normal periods may be like in the future and by including the potential for hydrologic extremes that can create flood risks and droughts. Water demand estimates are developed across water management system uses, including both the natural and socioeconomic systems, which include agriculture, municipal, environmental, and hydroelectric power generation. System operation boundaries include the natural system and the socioeconomic system. Acknowledging the uncertainties associated with future climate and associated potential impacts, the Omnibus Public Land Management of 2009 (Public Law 111-11) Subtitle F – SECURE Water authorized Reclamation to continually evaluate and report on the risks and impacts from a changing climate and to identify appropriate adaptation and mitigation strategies utilizing the best available science in conjunction with stakeholders.

SECURE Water and Reclamation's Response

The Omnibus Public Land Management Act of 2009 (Public Law 111-11) Subtitle F – SECURE Water was passed into law on March 30, 2009. Also known as the SECURE Water Act, the statute establishes that Congress finds that adequate and safe supplies of water are fundamental to the health, economy, security, and ecology of the United States although global climate change poses a significant challenge to the protection of these resources. Congress also finds that data, research, and development will help ensure future water supplies and that, although States bear the primary responsibility and authority for managing the water resources of the United States, the Federal Government should support the States, as well as regional, local, and tribal governments in this endeavor. With a focus on Reclamation's role as a Federal agency conducting water management and related activities, Reclamation is assessing risks to the water resources of the Western United States and developing strategies to mitigate risks to help ensure that the long-term water resources management of the United States is sustainable.

Section 9503 of the SECURE Water Act identifies the "Reclamation Climate Change and Water Program." Reclamation is addressing the authorities within the SECURE Water Act through a broad set of activities in conjunction with Secretarial Order 3289 establishing the U.S. Department of the Interior's integrated approach to addressing climate change and Secretarial Order 3297 establishing the WaterSMART Program and Research and Development activities all of which working in a coordinated manner with other Federal agencies, State, local, and tribal governments and nongovernmental organizations. Reclamation's activities represent a comprehensive and coordinated approach to identifying risks and impacts associated with current and future climate, working with stakeholders to identify and implement adaptation and mitigation strategies and collaborating to identify the best available science.

About this Report

This report is prepared by Reclamation in fulfillment of the requirements within section (§) 9503 of the SECURE Water Act. This report addresses the elements of § 9503 part (c), which are:

- (c)(1) – each effect of, and risk resulting from, global climate change with respect to the quantity of water resources located in each major Reclamation river basin

- (c)(2) – the impact of global climate change with respect to the operations of the Secretary in each major Reclamation river basin

- (c)(3) – each mitigation and adaptation strategy considered and implemented by the Secretary of the Interior to address each effect of global climate change

- (c)(4) – each coordination activity conducted by the Secretary with the U.S. Geological Survey (USGS), National Oceanic and

Atmospheric Administration (NOAA), U.S. Department of Agriculture (USDA), or any appropriate State water resource agency

This report is Reclamation's first report under the authorities of the SECURE Water Act and presents the current information available. Future reports will build upon the level of information currently available and the rapidly developing science relevant to address the authorities within the SECURE Water Act. Much of this report is based on synthesizing available literature and summarizing key findings from peer-reviewed studies. However, for element (c)(1), which includes focus on climate change implications for snowpack and natural hydrology, findings from an original assessment are introduced,[1] as this assessment has been conducted consistently for the eight Reclamation river basins, framed by a consistent set of Western United States climate projections. The report is based on making comprehensive and consistent assessments of risk across each of the major eight basins in a portfolio manner. Thus, results are comparable across the river basins assessed and, therefore, may support local level impact assessment; but further information likely is needed to inform local level decisionmaking. There are many other activities underway, focused on basin specific efforts in coordination with Reclamation stakeholders. Activities, including fiscal year (FY) 2009 WaterSMART Basin Studies (Colorado River Basin, Yakima River basin, Milk-St. Mary's River basin), the River Management Joint Operating Committee working within the Columbia River Basin, and the California Bay-Delta Conservation Plan as examples, may make different assumptions of how to include climate information, how to address uncertainties, and how to present results. Care must be taken to evaluate past and future time periods of comparisons and methodological choices when comparing the results presented within this report to other activities.

The report is organized as follows:

- Section 1: Provides an introduction and a brief overview to projected climate changes over the Western United States and implications for snowpack, runoff amount, and runoff timing (or seasonality). Section 1 also provides how the information for this report was developed as well as the uncertainties associated with the information.

- Sections 2 through 8: Provide basin-specific discussions of each major Reclamation basin identified within the SECURE Water Act including the basin setting, basin specific coordination, historical climate, historical

[1] Reclamation. 2011. *West-Wide Climate Risk Assessments: Bias Corrected and Spatially Downscaled Surface Water Projections.*

hydrology, projected future climate and hydrology, and implications for various water and environmental resources. Note that the SECURE Water Act separately identifies the Sacramento and San Joaquin Rivers as reporting basins; however, in this report, these two basins are discussed in concert given the interwoven nature of their water management issues (section 7).

- Section 9: Integrates findings from the basin-specific discussion to provide a west-wide perspective on projected climate and hydrologic changes. Geographic variations in projected changes are highlighted. The section also provides a brief inventory of uncertainties affecting the interpretation of these results, ranging from the uncertainties of generating global climate projections to simulating local hydrologic response.
- Section 10: Describes Reclamation's coordination of activities with respect to the SECURE Water Act Authorities.
- Section 11: Provides adaptation actions being implemented. This section provides a description of Reclamation activities with targets within the Department of the Interior High Priority Performance Goal for Climate.
- Section 12: Provides a listing references used within this document, directing the audience to a source for additional information.

Key Findings of this Report to Congress

A recent paper by the Congressional Budget Office[2] summarizes the current understanding of the impacts of climate change in the United States, including that warming will tend to be greater in the interior of the contiguous United States. Temperature and precipitation conditions over Western United States regional drainages are projected to change as the effects of global climate change are realized. Projections of future temperature and precipitation are based on multiple Global Circulation (or Climate) Models (GCMs) and various projections of future greenhouse gas emissions (GHG), technological advancements, and global population estimates. A survey of these models over any of the regional drainages shows that there is model consensus agreement reported between climate model projections

[2] Congressional Budget Office (CBO). 2009. *Potential Impacts of Climate Change in the United States*. Prepared at the request of the Chairman of the Senate Committee on Energy and Natural Resource. May 2009.

that temperatures will increase during the 21st century. There is less model consensus on the direction of precipitation change, with some climate models suggesting decreases while others suggest increases, although greater consensus does exist for some geographic locations (e.g., model consensus towards wetter conditions approaching the Northwestern United States and northern Great Plains and model consensus towards drier conditions approaching the Southwestern United States).

These findings are consistent with the historical and projected future climate information used in this report.[1] Much of the Western United States has experienced warming during the 20th century (roughly 2 degrees Fahrenheit (°F) in the basins considered within this report) and is projected to experience further warming during the 21st century with central estimates varying from roughly 5–7 °F, depending on location. As related to precipitation, historical trends in annual conditions are less apparent. Future projections suggest that the Northwestern and north-central portions of the United States gradually may become wetter (e.g., Columbia Basin and Missouri River basin) while the Southwestern and south-central portions gradually become drier (e.g., San Joaquin, Truckee, and Rio Grande River basins and the Middle to Lower Colorado River Basin). Areas in between these contrasts have median projected changes closer to no change, meaning they have roughly equal chances of becoming wetter or drier (e.g., Klamath and Sacramento basins and the Upper Colorado Basin). Note that these summary statements draw attention to median projected changes in temperature and precipitation, characterized generally across the Western United States. Inspection of the underlying ensemble of projection information shows that there is significant variability and uncertainty about these projected conditions both geographically and with time.

These historical and projected climate changes have implications for hydrology. Focusing first on snow accumulation and melt, warming trends appear to have led to a shift in cool season precipitation towards more rain and less snow, which has caused increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation in some Western United States locations. Hydrologic analyses-based future climate projections[1] suggest that warming and associated loss of snowpack will persist over much of the Western United States. However, there are some geographic contrasts. Snowpack losses are projected to be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges). It also appears that, in high altitude and high latitude areas, there is a chance that cool season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming), because precipitation increases are projected and appear to offset the snow-reduction effects of warming in these locations.

Geographic implications for future runoff are more complex than those for future snowpack. Although historical trends in annual or seasonal runoff appear to be weak, hydrologic analyses based on future climate projections[1] suggest that geographic trends should emerge as projected climate change develops. For example, the Southwestern United States to Southern Rockies are projected to experience gradual runoff declines during the 21st century (e.g., Rio Grande River basins and the Colorado River Basin) while the Northwest to north central United States are projected to experience little change through mid-21st century to increases by late-21st century (e.g., Columbia River Basin and Missouri River basin). Seasonally speaking, warming is projected to affect snowpack conditions as discussed above. Without precipitation change, this would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff. Results show that the degree to which this plays out varies by location in the Western United States. For example, cool season runoff is projected to increase over the west coast basins from California to Washington and over the north-central United States (e.g., San Joaquin, Sacramento, Truckee, Klamath, and Missouri basins and the Columbia Basin) and to experience little change to slight decreases over the Southwestern United States to Southern Rockies (e.g., Colorado River Basin and Rio Grande River basin). Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern United States, and Southern Rockies (e.g., Klamath, Sacramento, San Joaquin, Truckee, and Rio Grande River basins and the Colorado River Basin). However, north of this region, warm season runoff is projected to experience little change to slight increases (e.g., Columbia River Basin and Missouri River basin). It seems evident that projected increasing precipitation in the northern tier of the Western United States serves somewhat to neutralize warming-related decreases in warm season runoff whereas projected decreasing precipitation in the southern tier of the Western United States serves to amplify such warming-related decreases in warm season runoff.

While these results indicate how annual and seasonal natural runoff might be altered under climate change and in ways that geographically vary, it is not possible to infer water management impacts from simply these natural runoff changes alone. Water management systems across the West have been designed to operate within envelopes of hydrologic variability, handling variations from season to season and year to year. These systems were designed with local hydrologic variability in mind; and, as a result, their physical and operating characteristics vary in terms of storage capacity and conveyance flexibility. For example, the Colorado River Basin has a relatively large degree of storage relative to annual runoff when compared to California River basins and particularly relative to the Columbia River Basin. The ability to use storage resources to control future hydrologic variability and changes in runoff seasonality is an important consideration in assessing potential water management impacts due to natural runoff changes.

Within this report, there is a significant difference between the types of information presented with respect to risks from climate change on snowpack, hydrology, and water supplies and risks related to demand changes and the combined impacts on Reclamation's mission responsibilities. For example, the supply side is presented in a quantitative fashion with change metrics presented on annual runoff and seasonality of runoff. In contrast, for risks from demands and overall impacts, qualitative statements are made from literature synthesis at this time. Assessment of these water management impacts on a local level is a subject of ongoing activities within Reclamation's Basin Studies Program (Basin Studies and West-Wide Climate Risk Assessments) and other activities.

Finally, while this report summarizes potential future climate and hydrologic conditions based on best available datasets and data development methodologies, there are a number of analytical uncertainties that are not reflected in this report's characterization of future hydroclimate possibilities. Such uncertainties arise from analyses associated with characterizing future global climate forcings such as greenhouse gas emissions, simulating global climate response to these forcings, correcting global climate model outputs for biases, spatially downscaling global climate model outputs to basin-relevant resolution, and characterizing regional to basin hydrologic response to such downscaled climate projection information.

Collaborations

Reclamation collaborates with many entities to carry out its mission responsibilities, including other Federal agencies, States, and local governments as well as tribes and non-governmental organizations. To fulfill the authorities within the SECURE Water Act, a consistent process has been developed and utilized to begin the process of evaluating risks and impacts through collaboration with Federal agencies and their stakeholders. This includes Research and Development collaborations with the U.S. Geological Survey, National Oceanic and Atmospheric Administration, U.S. Army Corps of Engineers, and others through the Climate Change and Water Working Group. Other key collaborators include the National Drought Information System, State Climatologists, and the Western States Water Council and Western Governors Association. Reclamation also is implementing Secretarial Orders 3289 and 3297 to establish the integrated approach of addressing climate change and the WaterSMART Program. These two Secretarial Orders encourage collaboration with other Federal agencies, States, tribes, and local governments through sustainable water strategies and establishment of the Landscape Conservation Cooperatives and Climate Science Centers. Additional basin specific collaborations exist and are vital to the management of each basin identified within this report.

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1. Introduction

1.1 About Reclamation

Established in 1902, the Bureau of Reclamation (Reclamation) is best known for the dams, powerplants, and canals it constructed within the 17 Western United States. These water projects led to homesteading and promoted the economic development of the West. Today, Reclamation is the largest wholesaler of water in the United States and the second largest producer of hydroelectric power in the Western United States. Reclamation provides water to more than 31 million people, and provides one out of five Western farmers with irrigation water for 10 million acres of farmland that produce 60 percent (%) of the Nation's vegetables and 25 percent of its fruits and nuts. Reclamation's 58 powerplants annually provide more than 40 billion kilowatthours, which generate nearly a billion dollars in power revenues and produces enough electricity to serve 3.5 million homes.

Reclamation's mission is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Reclamation's vision is to protect local economies and preserve natural resources and ecosystems through the effective use of water. This vision is achieved through Reclamation's leadership, use of technical expertise, efficient operations, and responsive customer service. This includes developing and implementing efficient use of water through initiatives including conservation, reuse, and research; protecting the public and the environment through the adequate maintenance and appropriate operation of Reclamation's facilities; managing facilities to fulfill water user contracts and protect and/or enhance conditions for fish, wildlife, land, and cultural resources; work with customers and stakeholders to achieve mutual objectives; assist the Secretary of the Interior in fulfilling Indian Trust responsibilities; implement innovative, sound business practices with timely and cost-effective, measureable results; and promote a culturally diverse workforce that encourages excellence, creativity, and achievement.

1.2 Role of Climate Information in Reclamation's Water Resources Management

Water management includes the development and fulfillment of operating schemes on a variety of time scales from days to decades. For operating schemes that involve characterization of climate, Reclamation utilizes information in a variety of ways. Within water management planning, climate characterization informs estimations of future water supplies, future water demands, and boundaries of system operation. Climate information influences 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. Water demand estimates are developed across water management system uses, including both the natural and the socioeconomic systems, which include agriculture, municipal, environmental, and hydroelectric power generation. The boundaries of system operation include the natural system and the socioeconomic system.

1.3 About SECURE Water Act Section 9503: Reclamation Climate Change and Water Program

The Omnibus Public Land Management Act of 2009 (Public Law 111-11) Subtitle F – SECURE Water, known as the SECURE Water Act (SWA), passed into law on March 30, 2009. Per the statute, Congress finds that adequate and safe supplies of water are fundamental to the health, economy, security, and ecology of the United States although global climate change poses a significant challenge to the protection of these resources. Congress also finds that data, research, and development will help ensure that the continued existence of sufficient quantities of water support increasing populations, economic growth, irrigated agriculture, energy production, and the protection of aquatic ecosystems. Although the States bear the primary responsibility and authority for managing water resources of the United States, the Federal Government should support the States, as well as regional, local, and tribal governments to carry out nationwide data collection and monitoring activities, relevant research, and activities to increase the efficiency of use of water within the United States. With a focus on Reclamation's role as a Federal agency conducting water management and related activities, Reclamation is assessing risks to the water resources of the Western United States and developing strategies to mitigate risks to help ensure that the long-term water resources management of the United States is sustainable.

Section (§) 9503 of the SECURE Water Act identifies the "Reclamation Climate Change and Water Program" as a program that will:

§ 9503 (a) – General Objectives

Coordinate with the National Oceanographic and Atmospheric Administration and other appropriate Federal agencies to assess each effect of, and risk resulting from, global climate change with respect to the quantity of water resources located in a service area; and to ensure, to the maximum extent possible, that strategies are developed at watershed and aquifer system scales to address potential water shortages, conflicts, and other impacts to water users located at, and the environment of, each service area.

§ 9503 (b) – Required Elements

(b)(1) COORDINATE – Coordinate with United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and each appropriate State water resources agency to ensure use of best available science.

(b)(2) ASSESS – Work with the USGS and NOAA, and each appropriate State water resource agency to assess specific risks to the water supply of each major Reclamation river basin, including any risk relating to a change in snowpack, changes in the timing and quantity of runoff, changes in ground water recharge and discharge, and any increase in the demand for water as a result of increasing temperatures and the rate of reservoir evaporation.

(b)(3) ANALYZE – Analyze the extent that the risks to water supply will impact water deliveries to the contractors of the Secretary of the Interior, hydroelectric power generation facilities, recreation at Reclamation facilities, fish and wildlife habitat, applicable species listed as an endangered, threatened, or candidate species, water quality issues, flow and water dependent ecological resiliency, and flood control management.

(b)(4) DEVELOP STRATEGIES – Develop appropriate strategies to mitigate each impact of water supply changes in consultation with non-Federal participants. Strategies can relate to development of new water management, operating, or habitat restoration plans, water conservation, improved hydrologic models and other decision support systems, and ground water and surface water storage needs.

(b)(5) MONITOR – Work with the U.S. Department of Agriculture (USDA) and applicable State water resource agencies to develop a monitoring plan to acquire and maintain water resources data to strengthen the understanding of water supply trends and to assist in each assessment and analysis conducted.

§ 9503(c) – Reporting

Submit to the appropriate committees of Congress a report that describes
(c)(1) each effect of, and risk resulting from, global climate change with respect to the quantity of water resources located in each major Reclamation river basin;
(c)(2) the impact of global climate change with respect to the operations of the Secretary in each major Reclamation river basin, (c)(3) each mitigation and

adaptation strategy considered and implemented by the Secretary of the Interior to address each effect of global climate change, (c)(4) each coordination activity conducted by the Secretary with USGS, NOAA, USDA, State water resource agencies, and (c)(5) the implementation by the Secretary of the Interior of the monitoring plan.

1.4 About the Reclamation Climate Change and Water Program

Reclamation has developed programs that together represent a comprehensive approach to fulfilling its mission responsibilities and vision, given the added stress of climate change on the existing complexities of Western water management. Secretarial Order 3297 established the WaterSMART Program, and Secretarial Order 3289 set forth the U.S. Department of the Interior’s response to climate change through the establishment of the Landscape Conservation Cooperatives (LCCs) and Climate Science Centers (CSCs). Within these initiatives, Reclamation has developed the Basin Study Program and climate focused Research and Development Office activities. Together, these programs include four main components:

- Coordinating Federal agencies, States, Indian tribes, nongovernmental organizations (NGOs), and other stakeholders
- Enhancing climate change science
- Assessing the risks and impacts of climate change to water resources
- Implementing mitigation and adaptation strategies

Reclamation participates on the Interagency Climate Change Adaptation Task Force, co-chaired by the Council on Environmental Quality, the National Oceanic and Atmospheric Administration, and the Office of Science and Technology Policy. Reclamation also participates on the Water Resources and Climate Change Adaptation Workgroup and is supporting development of the National Action Plan for adaptation of freshwater resources management to climate change called for in the October 2010 Progress Report of the Task Force.

The Science and Technology Program includes coordination efforts as well as the development of data and research and development that bring the best scientific information to bear on assessments, analyzing impacts, and developing strategies. Reclamation has established, and continues to work within, the Climate Change and Water Working Group (CCAWWG), which brings together Reclamation, NOAA, USGS, United States Army Corp of Engineers (USACE), United States Environmental Protection Agency (EPA), and Federal Emergency Management Agency (FEMA) to identify and ultimately fill information gaps and needs of water managers. This includes, but is not limited to, Reclamation's direct funding of research projects and cooperative research through post-doctoral candidates. Reclamation works with the Office of Science and Technology Policy (OSTP) Subcommittee on Water Availability and Quality (SWAQ) and the Council on Environmental Quality (CEQ) to coordinate Federal research efforts. Through the CSCs, Reclamation contributes and works with partners to develop the science needs of the water management community.

The Basin Study Program includes implementation of the Basin Studies, West-Wide Climate Risk Assessments (WWCRAs) and participation in LCCs. These activities are complementary and represent a three-part approach to the assessment of climate change risks to water supplies and impacts to operations and the identification of adaptation strategies. The WWCRAs provide important baseline projections of risks to water supplies and potential operational impacts. Through the Basin Studies, Reclamation works with States, Indian tribes, local partners, and other stakeholders in a cooperative manner to evaluate the ability to meet future water demands within a river basin and to identify adaptation and mitigation strategies of the potential impacts of climate change. Through its participation within the LCCs, Reclamation is partnering with Federal, State, Indian tribes, and local governments as well as conservation groups and NGOs.

1.5 About this Report

This report is prepared by Reclamation in fulfillment of the statutory requirements of § 9503 of the SECURE Water Act and addresses § 9503 elements (c)(1)–(4). Much of this report is based on a literature synthesis, summarizing peer-reviewed studies that related to various reporting elements in the eight Reclamation river basins. For elements (c)(2) and (c)(3), which focus on climate change impacts for Reclamation operations and potential strategies to address such impacts, information presentation within this report is based solely on literature synthesis. For element (c)(1), which focuses on climate change implications for snowpack, hydrology, reservoir evaporations, and water demand, Reclamation recently completed an assessment that is introduced (Reclamation 2011a) and described in section 1.5.1. This additional effort assessed the effects of climate change where effects on snowpack and streamflow in the eight major Reclamation river basins (figure 1) framed a consistent set of Western United States climate projections. There is, thus, a significant difference between the types of information presented with respect to risks from climate change on snowpack, hydrology, and water

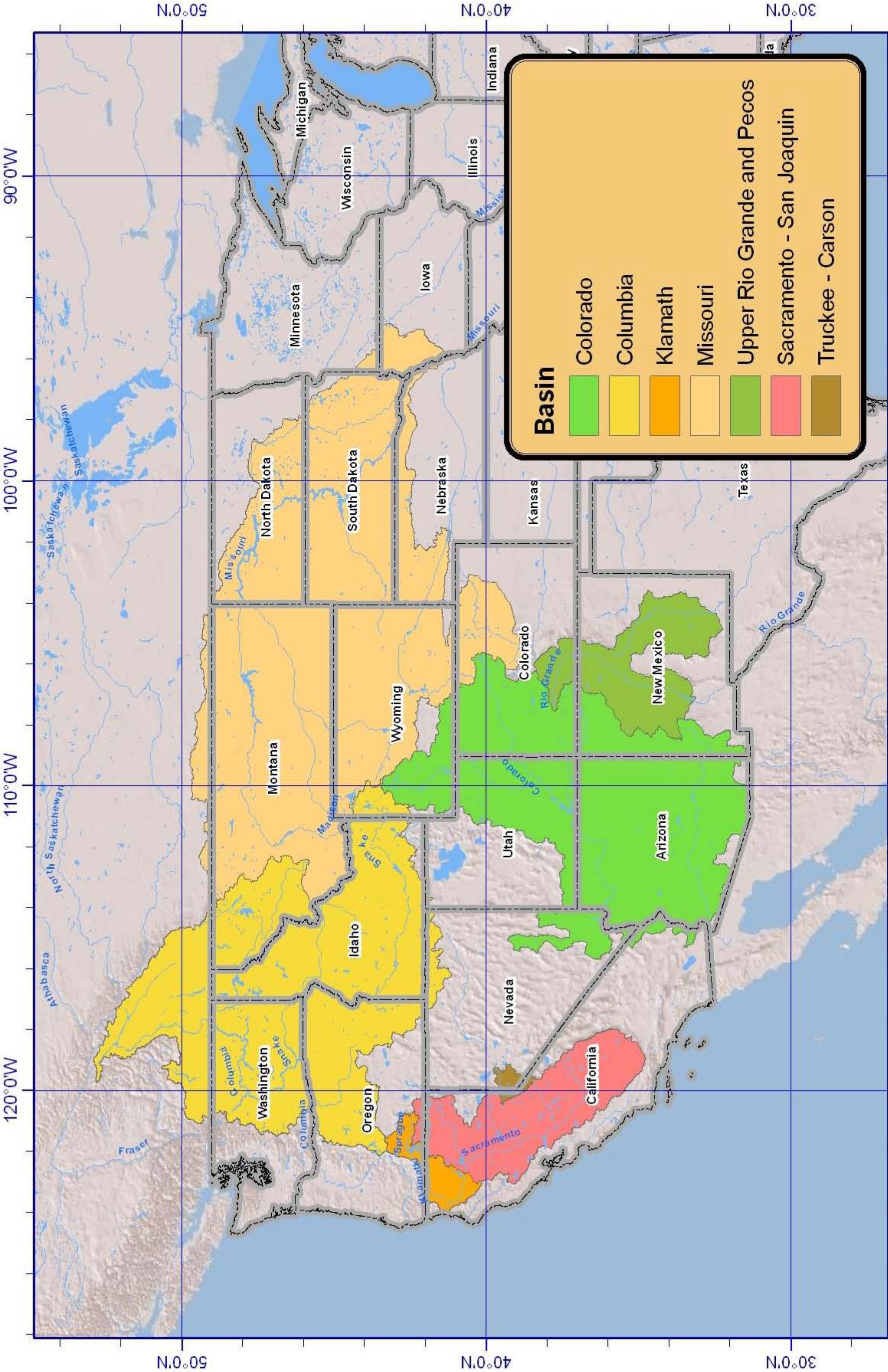


Figure 1. Eight major Reclamation River Basins listed in the SECURE Water Act, Section 9502.

supplies and risks related to demand changes and the associated impacts on operation dependent resources. The supply side, for example, is presented in a quantitative fashion with change metrics presented on annual runoff and seasonality of runoff. In contrast, for risks from demands and overall impacts to operational dependent resources, qualitative statements are made from literature synthesis at this time. In future reports, as Reclamation's Climate and Water Program more fully develops, quantitative presentations will be made for all risks; and impacts will be identified within the SECURE Water Act.

This report is meant to directly assess the requirements within § 9503 elements (c)(1)-(4) with the information currently available across the Western United States. This report is not intended to be a decisional document nor to make recommendations about future activities or priorities. The report is based on making comparable assessments of risk across each of the major eight basins in a portfolio manner. Thus, results are comparable across river basins and, as such, may support local level impact assessment; but further information likely is needed to inform local level decisionmaking. There are many other activities underway focused on basin specific efforts in coordination with Reclamation stakeholders. Activities, including fiscal year (FY) 2009 WaterSMART Basin Studies (Colorado River Basin, Yakima River basin, Milk-St. Mary's River basin), River Management Joint Operating Committee, and the Bay-Delta Conservation Plan as an example, may make different assumptions of how to include climate information, how to address uncertainties, and how to present results. Care must be taken to evaluate past and future time periods of comparisons and methodological choices when comparing the results presented within this report to other activities.

A recent paper by the Congressional Budget Office (CBO) (CBO 2009) presents an overview of the current understanding of climate change impacts in the United States, including that warming will tend to be greater in the interiors of the contiguous United States. Temperature and precipitation over Western United States regional drainages are projected to change as the effects of global climate change are realized. Projections of future temperature and precipitation are based on multiple Global Circulation (or Climate) Models (GCMs) and various projections of future greenhouse gas (GHG) emissions, technological advancements, and global population estimates. A survey of these models over any of the regional drainages shows that there is model consensus agreement reported between climate model projections that temperatures are projected to increase during the 21st century. There is less model agreement on the direction of precipitation change, with some climate models suggesting decreases while others suggest increases; although, greater consensus does exist for some geographic locations (e.g., consensus towards wetter conditions approaching the

United States Northwest and northern Great Plains and consensus towards drier conditions approaching the Southwestern United States).

These findings are consistent with the climate projection information used in Reclamation (2011a) and also used to frame this report (figures 2 and 3). Both maps display median projected changes in 30-year mean climate from those surveyed within a collection of climate projections. The map also displays these middle changes distributed over the Western United States, focusing on changes by the end of the 21st century relative to the middle 20th century.

Although magnitude of changes in the earlier part of the 21st century will be smaller, the direction of the geographic change is still generally the same throughout the 21st century (e.g., towards warmer conditions or towards wetter or drier conditions).

The widespread projected warming over the Western United States would logically lead to a reduced cool season accumulation of snowpack (i.e., late autumn to early spring), increased cool season rainfall-runoff, and decreased snowmelt runoff during late spring and summer (CBO 2009; Reclamation 2011a). Warming alone also is expected to cause a decrease in annual runoff by increasing watershed evapotranspiration.

Precipitation change, depending on seasonality and type (i.e., rain or snow), could somewhat offset or amplify such warming-related effects depending on whether the change is towards wetter or drier conditions. Given that warmer air can hold more moisture, global precipitation is expected to increase as global temperatures increase. However, regional variation of precipitation change is possible and depends on regional atmospheric circulation response to global warming. Based on current climate model simulations, results suggest that historically "wet" regions of the world may become wetter while historically "dry" regions may become drier (Intergovernmental Panel on Climate Change [IPCC] 2007). The latter appears to be a result of expanded Hadley Circulation and broadening atmospheric subsidence zones over desert regions such as northern Mexico and the Southwestern United States. The precipitation projections used in this report reveal such a pattern over the Western United States (figure 3). The projections suggest that basins located at higher latitudes (i.e., towards the United States-Canada border) generally should experience wetter conditions; whereas, basins at lower latitudes (e.g., towards the United States-Mexico border) and towards the greater American Southwest generally should experience drier conditions. Thus, over the American Southwest, both projected precipitation reduction and warming conditions both might be expected to contribute to annual runoff reductions.

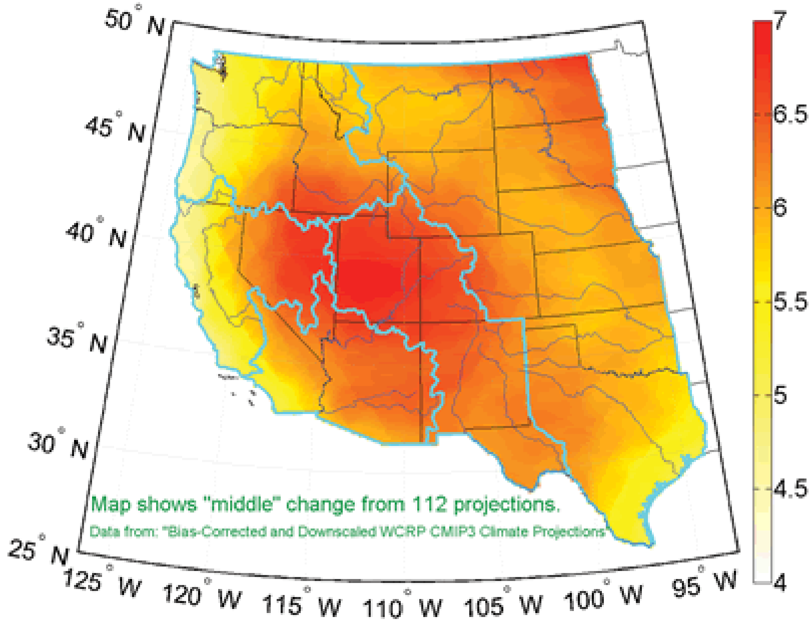


Figure 2. Projected median temperature change in degrees Fahrenheit (°F)(of 112 climate projections) over the Western United States, 2070–2099 relative to 1950–1979.

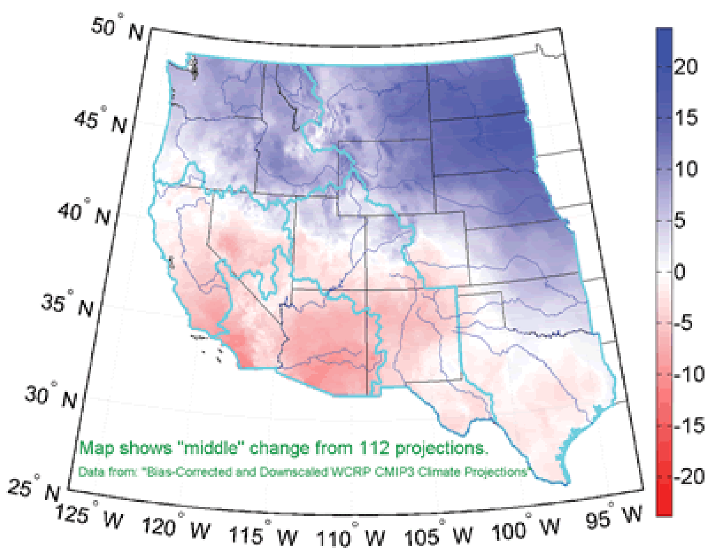


Figure 3. Projected median percentage precipitation change (of 112 climate projections) over the Western United States, 2070–2099 relative to 1950–1979.

Over the Pacific Northwest and northern Great Plains, precipitation increases tend to increase annual runoff, countering how warming tends to decrease annual runoff via increased watershed evapotranspiration. Regarding seasonal streamflow timing, the impact on basins traditionally experiencing cool season snowfall is not entirely dependent on annual precipitation change. For these basins, warming still could create more cool-season rainfall as opposed to snowfall and, thus, shift the timing of streamflow towards more runoff occurring during the cool season and less during the warm season. Focusing on extreme events instead of water supply statements, the CBO report (2009) also suggests that warming will lead to more intense and heavy rainfall interspersed with longer, relatively dry periods.

Sections 2–8 of this report are devoted to basin-specific narratives that each address § 9503 elements (c)(1)–(3). Section 9 then synthesizes key messages from these basin-specific assessments, highlighting common themes across the Western United States. Section 10 addresses § 9503 element (c)(4), describing Reclamation's coordination with USGS, NOAA, USDA, State water resource agencies, and others on activities to ensure water resources management of the United States is sustainable. Lastly, section 11 presents some current actions Reclamation is taking to adapt to the potential impacts of climate change.

1.5.1 Reclamation (2011a) Quantitative Risks to Water Supply

Climate change risks to future water supplies are quantified in this report based on assessments described in a companion document entitled West-Wide Climate Risk Assessments: BCSD Surface Water Projections (Reclamation 2011a). The assessments involve developing hydrologic projections associated with a large collection of the global climate projections featured in the IPCC Fourth Assessment (IPCC 2007) and developed as part of the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3); CMIP3 projections are regarded as the best available information source for describing future global climate possibilities. To support hydrologic assessment over the Western United States, the CMIP3 climate projections were bias-corrected and spatially downscaled (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections). In total, 112 climate projections were considered in Reclamation (2011a) and translated into hydrologic projections using watershed applications of the Variable Infiltration Capacity (VIC) macroscale hydrology model (developed at the University of Washington). Outputs from the VIC models include snowpack and runoff distributed over the watershed. The latter then was routed to reporting locations as featured in this report.

There are methodologies other than those employed within Reclamation (2011a) that could be employed to assess water supply risks, including methods that utilize Global Circulation Models in different ways or do not use them at all. Uncertainties associated with using GCMs are presented within section 1.6 with a greater discussion and presentation available within Reclamation 2011a. Approaches do exist to assess future risks on water supplies that do not rely upon the uncertainties associated with Global Climate Models, for example, a statistical representation of future potential water supplies through the use of stochastic analysis. Stochastic approaches have been proposed by Anagnostopoulos et al. (2010) as a way to recognize that uncertainty is an intrinsic component of the processes of interest. Stochastic approaches using observed and paleo-reconstructed streamflow records are being utilized in addition to the direct use of GCM information within the WaterSMART Colorado River Basin Study. Reclamation will continue to evaluate how to include the best available science to ensure that future assessments of risks and impacts for reporting and decisionmaking processes are sound and responsible.

1.6 Uncertainties

1.6.1 Sources of Uncertainty

This report summarizes analyses on potential future climate and hydrologic conditions in the Western United States. The information presented is gathered from Reclamation (2011a) as well as other peer-reviewed literature and reflects the use of best available datasets and data development methodologies. However, best available science includes a number of analytical uncertainties that are not reflected in this report’s characterization of future hydroclimate possibilities, including uncertainties associated with the following analytical areas.

1.6.1.1 Global Climate Forcing

Although this report considers climate projections representing a range of future greenhouse emission pathways (Reclamation 2011a), the uncertainties associated with estimating these pathways are not explored in this analysis. Such uncertainties include those introduced by assumptions about technological and economic developments, globally and regionally; how those assumptions translate into global energy use involving GHG emissions; and biogeochemical analysis to determine the fate of GHG emissions in the oceans, land, and atmosphere. Also, not all of the uncertainties associated with climate forcing are associated with GHG assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., figure SPM-2 in IPCC 2007). Note that this report uses an ensemble of downscaled climate and hydrologic projections

(Reclamation 2011a) that stem from global climate projections collectively reflecting three scenarios of GHG emissions (IPCC 2000): B1 (lower emissions path), A1B (middle emissions path), and A2 (greater emissions path). For the purposes of this report, results from these projections are pooled based on the assumption that these scenarios are equally plausible and the lack of information to suggest otherwise. As shown in IPCC 2007, for early to middle 21st century, the projections ensembles (temperature and precipitation) are similar for each scenario, suggesting that choice of emissions scenario does not significantly influence projection uncertainty in this timeframe. However, by the end of the 21st century, the scenario-specific ensembles of temperature projections do start to diverge, with the A2 scenario leading to substantially larger warming than the B1 scenario.

1.6.1.2 Global Climate Simulation

This report considers climate projections produced by state-of-the-art coupled ocean-atmosphere climate models. Even though these models have shown an ability to simulate the influence of increasing GHG emissions on global climate (IPCC 2007), there are still uncertainties about the scientific community's understanding of physical processes that affect climate, including how to simulate such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycle, vegetative and other biological changes). Uncertainties in simulating regional atmospheric circulation response to changes in global climate forcing are relevant in projecting effects on regional to local weather patterns (e.g., effects on storm track positions approaching the west coast, effects on North American Monsoon over the Colorado River Basin and Rio Grande basins, or effects on interplay between Pacific, Arctic, and Gulf of Mexico air masses affecting precipitation conditions over the Great Plains). In addition, the process of specifying initial climate system conditions at the beginning of 20th and 21st century simulations (e.g., heat distribution throughout the oceans) permits projections to stem from different "distributed initial conditions," which also contributes to projection uncertainties at the regional scale (Hawkins and Sutton 2009), particularly for precipitation (Hawkins and Sutton 2010). Finally, it is noted that this report does consider these uncertainties by surveying projection information from a multimodel ensemble, similar to the approach used in the IPCC Fourth Assessment (IPCC 2007). However, as noted in the Fourth Assessment, even this "ensemble of opportunity" may not cover the entire range of uncertainty associated with global climate simulation.

1.6.1.3 Climate Projection Bias Correction

Analyses (Reclamation 2011a) presented within this document assume that GCM biases toward being too wet, too dry, too warm, or too cool should be identified and accounted for prior to use in implications studies like sensitivity analyses. However, the procedure to remove biases in climate projections relative to a historical baseline can affect the apparent "climate change," from a historical period to a future period, expressed by the projections (biased versus bias-corrected). This has been shown within Reclamation (2011a), where the method for bias correcting the climate projections appears to have altered projected precipitation changes to be slightly wetter over much of the Western United States in the bias-corrected projections.[3] This, in turn, leads to less adverse future hydrologic changes than they would have been if they had been based on changes from the biased climate projections.

1.6.1.4 Climate Projection Spatial Downscaling

The analyses presented within this report (Reclamation 2011a) utilize climate projections that have been downscaled using a nondynamical and relatively simple spatial disaggregation technique (Wood et al. 2002). Although this technique has been used to support numerous water resources impacts studies, uncertainties remain about the limitations of empirical downscaling methodologies relative to more sophisticated dynamical methods that rely on coupling outputs from global climate models to the inputs of finer resolution regional climate models. Nevertheless, the spatial disaggregation technique was used due to the ease in applying it to a large collection of climate projections over the Western United States for the 21st century and, thus, to better sample the uncertainty due to global model simulations compared to what feasibly could be done using dynamical methods.

1.6.1.5 Watershed Vegetation Changes Under Climate Change

In Reclamation (2011a) and related literature sources cited, the chosen approach for assessing hydrologic effects under projected climate changes is to use a "surface water hydrologic" model that computes hydrologic conditions given changes in weather while holding other watershed features constant. Vegetation features might be expected to change as climate changes that, in turn, would affect runoff through changes to evapotranspiration and infiltration processes.

1.6.1.6 Quality of Hydrologic Model Used To Assess Hydrologic Effects

In Reclamation (2011a) and most of the cited literature sources, the chosen approach for assessing hydrologic effects typically has involved using "surface

[3] When 25th, 50th, and 75th percentile precipitation changes were identified within the ensemble of projections over the Western United States, it was found that percentage changes from bias-corrected projections were generally zero to a few percent greater than percentage changes from the biased projections (figure 9 of Reclamation 2011a).

water hydrologic" models, which attempt to account for the shallow surface layers of the watershed without considering the full range of watershed ground water processes and interaction with surface water conditions. Further, these surface water hydrologic models generally are not designed to represent the water balance processes of large water bodies (e.g., Lake Tahoe for the Truckee River basin). Thus, while the direction of projected hydrologic changes is expected to be a robust result from these hydrologic models, the magnitude of change is less certain and possibly affected by the omission of key hydrologic processes related to ground water and/or large water bodies. For the results from Reclamation (2011a), further uncertainty is introduced by how the models were shown to imperfectly reproduce historical runoff conditions. Some of these imperfections could be reduced through refined redevelopment, or "calibration," of the models.

To support such model refinement, preliminary activities might include updating naturalized flow datasets, where observed flows have been adjusted for the effects of upstream reservoir operations, water diversions, return flows, and other impairments. Updates ideally would focus on extending periods of record, expanding the list of locations, and the uniformity of methods used to construct such datasets. As it is, available natural flow datasets across the eight reporting basins are specified for inconsistent periods and for a limited list of locations. Completing such updates also would set up the ability to consistently report on historical streamflow trends in the eight major reporting basins, where trends are based on historical natural flow estimates. This report doesn't include such information and, instead, focuses on changing information from runoff simulations, as described above.

1.6.2 Centrally Projected Effects Within the Range of Possibility

This report is intended to communicate to the appropriate committees of Congress, as identified within the SECURE Water Act, future hydrology associated with a collection of current climate projections. In this respect, the report represents projection uncertainties associated with climate forcing (i.e., greenhouse gas emissions) and global climate simulation (given that the collection of projections represents a collection of atmospheric ocean general circulation models). However, subsequent uncertainties are not quantified in this report, namely those associated with how to bias correct and spatially downscale global climate projections and how to assess hydrologic response. The information developed in support of this report may help inform local and regional water resources adaptation and mitigation actions. Specific water resources adaptation and mitigation strategy development may identify and incorporate the most significant adaptation risks and opportunities.

This report presents information on centrally projected (median) changes in future climate (i.e. temperature and precipitation) and associated effects on hydrology (i.e., April 1st snowpack and streamflow). The report acknowledges that median projected changes exist within an ensemble of projected possibilities. The central tendency, as well as the distribution of possibilities, conveys information about future conditions and potential risks. Communication of median change from historical conditions is relatively simpler than the communication of the complexities associated with change distributions, however, consideration of the full range of possibilities can help inform situations where "low probability" climate changes may have "highly significant" impacts. Such information may inform specific adaptation strategy development efforts that can incorporate risk-management in conjunction with appropriate State, local, tribal governments and nongovernmental organizations utilizing methods to identify, assess, and prioritize options to reduce vulnerability to potential environmental, social, and economic implications of change.

Readers interested in the range of projections are referred to the supporting technical report describing the development of hydrologic projections (Reclamation 2011a). The technical report presents both central tendency changes, as are presented within this report, along with the interquartile range of changes distributed about these medians (figure 4).

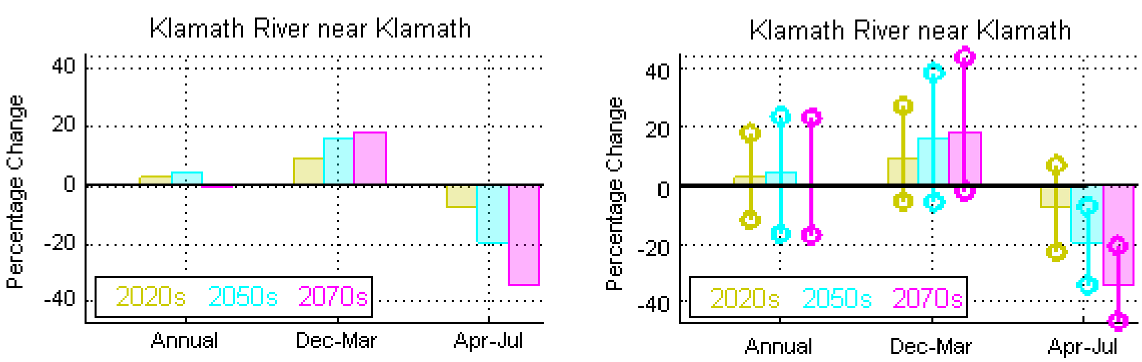


Figure 4. Approach to displaying results in this report (focus on median changes, left panel) versus Reclamation 2011a (focus on range of changes, right panel, showing 25th percentile, median, 75th percentile changes).

2. Basin Report: Colorado

2.1 Basin Setting

The Colorado River Basin is located in the Southwestern United States and occupies an area of approximately 250,000 square miles (figure 5). The Colorado River is approximately 1,400 miles long and originates along the Continental Divide in Rocky Mountain National Park in Colorado. Elevations in the Colorado River Basin range from sea level to over 14,000 feet above mean sea level (msl) in the mountainous headwaters. The Colorado River is a critical resource in the West because seven Western States (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) depend on it for water supply, hydropower production, flood control, recreation, fish and wildlife habitat, and other benefits. In addition, the United States has a delivery obligation to Mexico for certain waters of the Colorado River pursuant to the 1944 Treaty with Mexico.

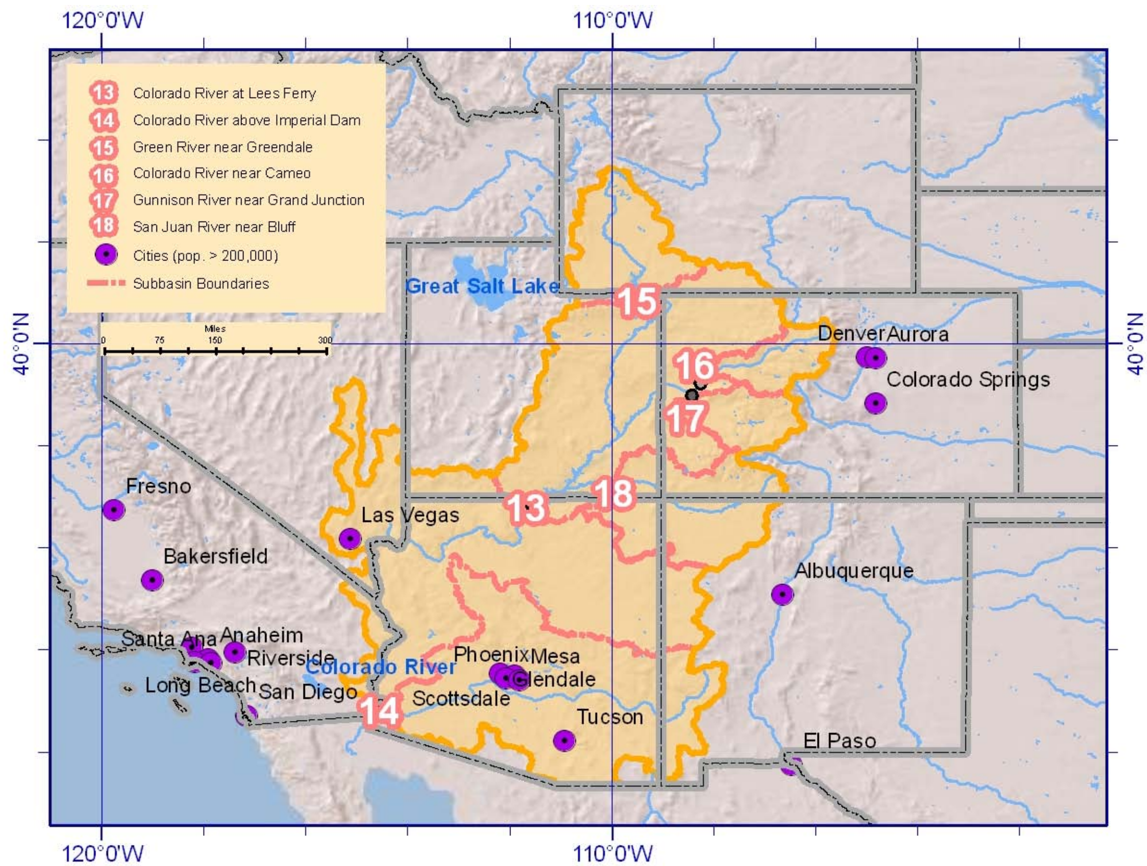


Figure 5. Colorado River Basin and runoff-reporting locations for this report.

Climate varies significantly throughout the Colorado River Basin. A majority of the Colorado River Basin is comprised of arid or semiarid rangelands, which historically receive less than 10 inches of precipitation per year. In contrast, many of the mountainous areas that rim the northern portion of the Colorado River Basin receive, on average, over 40 inches of precipitation per year. Most of the total annual flow in the Colorado River Basin results from natural runoff from mountain snowmelt. Because of this snowmelt process, natural flow[4] is historically highest in the late spring and early summer and diminishes rapidly by midsummer. While flows in late summer through autumn sometimes increase following rain events, natural flow in the late summer through winter is generally low, compared to snowmelt runoff in the spring and early summer.

The natural flow in the Colorado River Basin is highly variable from year to year due to variability in climatic conditions. About 85% of the Colorado River Basin annual runoff originates in approximately 15% of the watershed—in the mountains of Colorado, Utah, Wyoming, and New Mexico. Over the past approximately 100 years (1906–2010), the annual natural flow measured at the Lees Ferry gauging station (located approximately 16 miles downstream from Glen Canyon Dam) has ranged from a low of 5.5 million acre-feet (maf) to a high of 25.5 maf, while averaging 15.0 maf.

The flow in the Colorado River above Lake Powell (formed by Glen Canyon Dam), located along the Utah-Arizona border, historically reaches its annual maximum during the April–July period. During the summer and fall, thunderstorms occasionally produce additional peaks in the river. However, these flows are usually smaller in volume than the snowmelt peaks and of much shorter duration. Downstream from Lake Powell, the Colorado River gains additional waters (on average, approximately 1.3 maf) from tributaries, ground water discharge, and occasional flash floods from side canyons.

Apportioned water in the Colorado River Basin totals 16.5 maf. The Colorado River Compact of 1922 apportioned to the Lower Division States (Arizona, California, and Nevada) and the Upper Division States (Colorado, New Mexico, Utah, and Wyoming), in perpetuity the beneficial consumptive use of 7.5 maf per year. The 1944 Treaty with Mexico allocated 1.5 maf annually to Mexico. Use (consumptive uses and losses—e.g., reservoir evaporation) in the Colorado River Basin averaged approximately 15.4 maf over the 10-year period from 1998–2007. The Upper Division States have not fully developed their apportionment, and their

[4] The natural flow of the river represents an estimate of runoff that would exist in a natural setting, without storage, alteration or depletion by humans.

use averaged approximately 4.3 maf over that period. The total storage capacity in the Colorado River system is over four times the river's average annual runoff or about 60 maf. However, the two largest reservoirs in the system, Lake Powell and Lake Mead (formed by Hoover Dam), located on the Arizona-Nevada border, account for approximately 85% of this storage capacity. For a full description of the Secretary of the Interior's management of the Colorado River from 1979–2008, Reclamation has recently completed and released The Colorado River Documents 2008, available at http://www.usbr.gov/lc/region/programs/CRdocuments2008.html.

Reclamation collaborates and consults with a diverse body of interested stakeholders, including Federal, State and local agencies, environmental organizations, Native American tribes and communities, and the general public on a variety of water resource operations and planning activities related to the Colorado River Basin. In particular, the Lower and Upper Colorado Regions are leading the WaterSMART Colorado River Basin Water Supply and Demand Study (the Colorado River Basin Study)—a comprehensive study to define current and future imbalances in water supply and demand in the Colorado River Basin and the adjacent areas of the seven Colorado River Basin States (Basin States) that receive Colorado River water for approximately the next 50 years—and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Colorado River Basin Study, funded under the WaterSMART Basin Study Program and cost-shared by water resource agencies in the Basin States, is being conducted in a transparent, open manner to solicit and incorporate input from stakeholders throughout the Colorado River Basin.

The risk assessment presented in this report was prepared by Reclamation to provide coordinated and consistent information focused on the future risks to water supply throughout the eight Reclamation river basins as identified within the introduction. In contrast, the Colorado River Basin Study is focusing on a more detailed, basin-wide assessment of risk to Colorado River Basin resources from future water supply and water demand imbalances and identification and evaluation of options and strategies to resolve future imbalances and mitigate risks. While not engaged in the risk assessment presented in this report, the Basin States and other stakeholders are heavily engaged in the Colorado River Basin Water Supply and Demand Study.

The Colorado River Basin Study contains four major phases: water supply assessment, water demand assessment, system reliability analysis, and development and evaluation of opportunities for balancing supply and demand. A scenario planning process has been undertaken to provide a framework to incorporate the high degree of uncertainty in the assessment of future water supply and water demand. This process, which included input from stakeholders throughout the Colorado River Basin, was used to develop a broad range, yet manageable number, of plausible scenarios of future supply and demand. Four water supply scenarios have been formulated and quantified, one of which incorporates future climate projections from GCMs using similar techniques as used in this report. The remaining three water supply scenarios utilize stochastic approaches applied to observed and paleoreconstructed streamflow records. Six water demand scenarios also have been identified that incorporate plausible future trajectories related to demographics and land use, technology and economics, and social and governance factors.

As of the publication date of this report, three of the four water supply scenarios have been quantified and analyzed in the Colorado River Basin Study. For the scenario informed by GCMs, remaining work entails the accounting and adjusting for biases introduced by the chosen methodologies, likely a result of the uncertainties described in section 1.6. Work is ongoing to complete the quantification of the demand scenarios. In addition, the remaining phases of the study (system reliability analysis and the development of opportunities to resolve supply and demand imbalances) have been initiated.

Some methodological differences with respect to the technical approach to develop streamflow projections informed by GCMs (i.e., generation of daily weather forcings and the application of a secondary bias correction) as well as the presentation of results (i.e., selection of the time periods of the baseline climate and future analysis) exist between this report and the Colorado River Basin Study. Therefore, results between the two efforts will not be identical; however, the ongoing work in the Colorado River Basin Study will be used to inform future reports under Section 9503 of the SECURE Water Act.

2.2 Historical Climate

Over the course of the 20th century, warming has been prevalent over the Colorado River Basin. Precipitation trends within the Colorado River Basin are more uncertain. Based on data available from the Western Climate Mapping Initiative, the change in 11-year annual mean during the 20th century is roughly +1.2 degrees Celsius (°C) (2.16 degrees Fahrenheit [°F]) for the Upper Basin and +1.7 °C (+3.06 °F) for the Lower Basin (figure 6, top panel). These data are consistent with other studies (e.g., Weiss and Overpeck 2005 and Easterling 2002) that have shown increase of 1-3 °C [1.8–5.4 °F] since the 1970s in the Western United States (Cayan et al. 2001) and over the San Juan Mountains, a net warming of 1 °C between 1895–2005 with most warming during 1990–2005

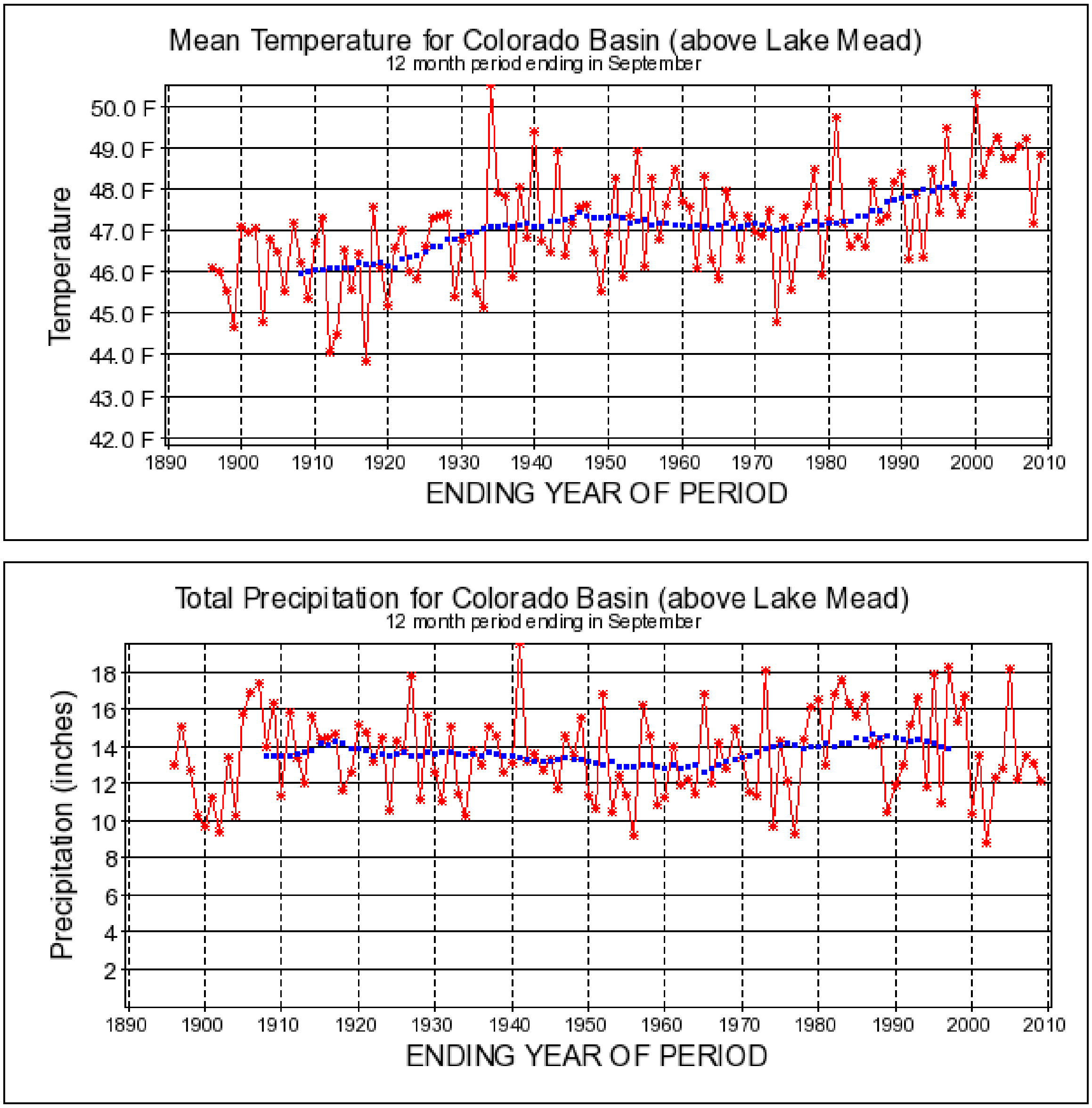


Figure 6. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Colorado River Basin above Lake Mead.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system (Daly et al. 2004; Gibson et al. 2002).

(Rangwala and Miller 2010). Additionally, the United States Historical Climate Network (USHCN) stations indicate that annual mean and minimum temperature have increased 1–2 °C (1.8–3.6 °F] for most of the Lower Basin for 1900–2002 (Groisman et al. 2004); these same stations suggest that spring minimum temperatures have increased 2–4 °C [3.6–7.2 °F] during the same period. The changes in temperature are not equal by seasons: at Lower Basin USHCN stations, for the periods 1930–1997 and 1950–1997, winter temperatures have increased up to 4 °C [7.2 °F] (Mote et al. 2005). Since 1951, the summer temperatures have warmed 0.9 °C [1.6 °F], with very high confidence that the warming exceeds levels of natural climate variability (Hoerling and Eischeid, 2007).

The warming of the Colorado River Basin has not been steady in time throughout the 21st century. Rather, the Upper Colorado River Basin region average temperatures indicate a warming period during the early 20th century followed by a flat, or even cooling, period from the 1940s to the 1970s and then warming from the 1970s to present (figure 6**)**. Hence, the range of warming identified above by region and by time period is indicative that the magnitude of analyzed temperature trends vary from study to study depending on the period of analysis.

Precipitation analyses also have been conducted to assess historical precipitation trends over the Colorado River Basin. In summary, variability appears to dominate the historical precipitation record, and the large variability on the multidecadal time scale makes trend detection difficult (figure 6, bottom panel). However, when shorter periods have been considered, seasonal and more localized trend assessments have shown significant changes. For example, during the periods 1930–1997 and 1950–1997, winter precipitation increased in the Lower Colorado River Basin, observed at over 60% of USHCN stations prior to the onset of extended drought in the late 1990s. Winter precipitation (November–March) has increased at the majority of NOAA Coop Network stations during 1950–1999 (Regonda et al. 2005). Whether these findings are a result of multidecadal variability or long-term climate trends is still a matter in question. From 1900–2002, a mix of annual precipitation trends in USHCN stations in the Lower Colorado Region were evaluated, showing declines in the western part of the region but slight increases in the eastern part of the region (Groisman et al. 2004).

2.3 Historical Hydrology

Coincident with the trends in historical climate, the Western United States experienced a general decline in spring snowpack, reduced fractions of winter precipitation occurring as snowfall, and earlier snowmelt runoff. Reduced snowpack is indicated by analyses of snow water equivalent (SWE) measurements at 173 Western United States stations over the period 1948–2001 (Knowles et al. 2007). Since 1950, SWE has declined at over half of the Western United States stations (Regonda et al. 2005). Among those stations, there was no regional consensus among SWE trends over southern Montana to Colorado. Basins above about 2,500 meters (8,202 feet) showed little change in peak streamflow or in monthly SWE.

SNOTEL stations (USDA-Natural Resource Conservation Service [NRCS] automated Snowpack Telemetry) usually are located in mountain environments and make observations and collect data at higher elevations. Strong correlations exist between temperature, winter season snowmelt events, and total April 1st SWE at SNOTEL stations (Mote 2006). These correlations imply that warming results in less April 1st SWE through the increased frequency of melt events and are consistent with evidence of declining spring snowpack across North America as stated in the IPCC Fourth Assessment Report (IPCC 2007). Other studies, including Clow (2010), Hamlet et al. (2005), and Stewart et al. (2004), document decreasing snowpack and earlier runoff in the Colorado River Basin.

Naturalized streamflow data (defined in section 1.6.1) have been estimated at 29 USGS gauge locations within the Colorado River Basin from 1906–2005.[5] These data indicate that the timing and magnitude of streamflow within the Colorado River Basin is changing (Miller and Piechota 2008; Regonda et al. 2005). Trends in streamflow indicated increased runoff between November and February and decreased runoff between April and July. April–July runoff traditionally is recognized as the peak runoff season in the Colorado River Basin, as mountain snowpack melts and contributes to basin inflow. The period of 2000–2010 marked the lowest 11-year period on the Colorado River Basin since 1906 in terms of annual natural flow at Lees Ferry.

Although apparent trends in the timing and magnitude of streamflow have been observed, runoff variability continues to be a dominant factor affecting Colorado River water management. The Colorado River Basin, as well as the Southwestern

[5] http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.

United States in general, has experienced year-to-year variations in runoff throughout the period of instrument records. Conditions can vary significantly from spells of surplus, which cause flooding conditions, to periods of drought and arid climate conditions (e.g., Balling and Goodrich 2007; Seager et al. 2007). For example, an examination of 81 years (1923–2004) of USGS and Palmer Hydrological Drought Index (PHDI) streamflow data from the Upper Colorado River Basin from the USGS and PHDI values from the NCDC suggests that roughly 11 runoff droughts occurred on the Colorado River near Cisco, Utah, and Green River, near the Green River, Utah, gauges (Piechota et al. 2004). When compared with tree ring reconstructions of streamflow, the drought spanning 1999–2004 ranked the seventh worse in the last 500 years. Tree ring reconstructions show that the Colorado River Basin often experienced long-term, severe droughts prior to instrumental records (Woodhouse et al. 2006). One of these reconstructions (Meko et al. 2007) suggests that the lowest 25-year average flow during the period of tree ring records occurred roughly during 1130–1154 and appeared to feature an average annual runoff equal to about 87% of the observed average during 1906–2004.

Several studies suggest that many observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than precipitation effects (Lettenmaier et al. 2008). However, any such apparent trends or changes in climate over regional drainages like the Colorado River Basin are sensitive to the uncertainties of station measurements as well as the period of analysis and location being analyzed. As related to the broader Western United States region, historical trends in temperature, precipitation, snowpack, and streamflow might be explained partially by anthropogenic influences on climate (Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009). However, it remains difficult to attribute historical trends in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends concerning precipitation (Hoerling et al. 2010) and for trends assessed at the basin scale rather than at the Western United States scale (Hidalgo et al. 2009). In addition, recent research has shown that dust deposits on snow can advance the timing of runoff and perhaps reduce streamflow (Painter et al. 2010). This further complicates interpretation of historical climate change trends in the Colorado River Basin, as well as future trends given that such dust effects are not included in either the future climate or hydrologic simulations discussed in this report.

2.4 Future Changes in Climate and Hydrology

This section summarizes results from studies focused on future climate and hydrologic conditions within the Colorado River Basin. Section 2.4.1 focuses on results from Reclamation (2011a) that were produced for a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document. During the past several decades, many studies have been conducted on projected future hydroclimate of the Colorado River Basin, and a subsequent discussion is offered on the key findings and themes from these studies.

2.4.1 Projections of Future Climate and Hydrology from Reclamation (2011a)

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the persepctive of basin-average and, secondly, as those climate conditions are distributed throughout the basin. Discussion then segues to a summary of snow-related effects under future climate conditions as they may be distributed throughout the basin. Subsequently, a discussion is offered on how climate and snowpack changes effect annual and seasonal runoff, as well as acute runoff events relevant to flood control and ecosystems management.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Colorado River Basin may increase steadily during the 21st century (figure 7). For example, in the Upper Colorado River Basin , the basin-average mean-annual temperature is projected to increase by approximately 6–7 °F during the 21st century. When conditions are averaged across both the Upper and Lower Colorado River Basins, the expected increase is roughly 5–6 °F.

The same climate projections suggest that mean-annual precipitation, averaged over the basin, is only expected to change by a small amount during the 21st century. Annual variability in precipitation is expected to persist within the

Colorado River Basin, and the basin likely will continue to experience both wet and dry periods throughout the 21st century (figure 8).

Some geographic complexities of climate change emerge over the Colorado River Basin when climate projections are examined location by location, particularly for precipitation change. For example, consider the four decades highlighted on figure 7 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. In this case, the 1990s are considered to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, temperatures in the Upper Colorado River Basin (figure 8, top left panel) are generally cooler in the north and along the mountainous rim.

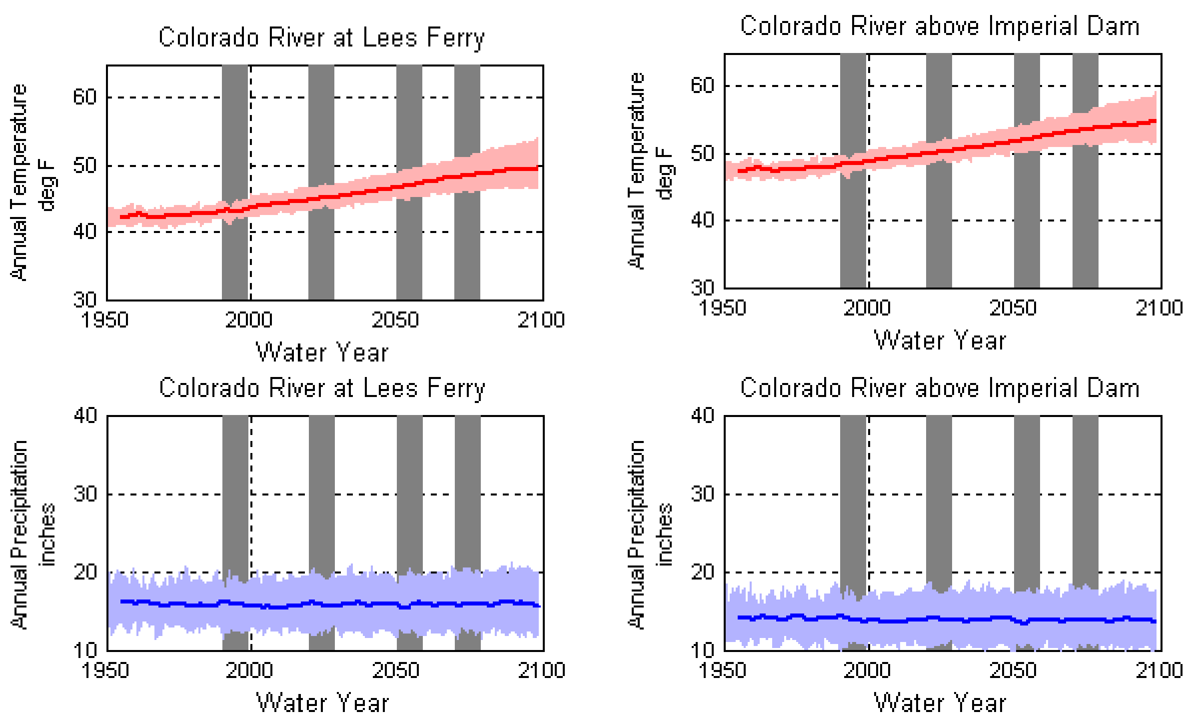


Figure 7. Simulated annual climate averaged over Colorado River subbasins.

Figure 7 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099. Vertical gray bars highlight four decades of interest used to characterize basin decadal changes in temperature, precipitation, snowpack and runoff (shown on subsequent figures).

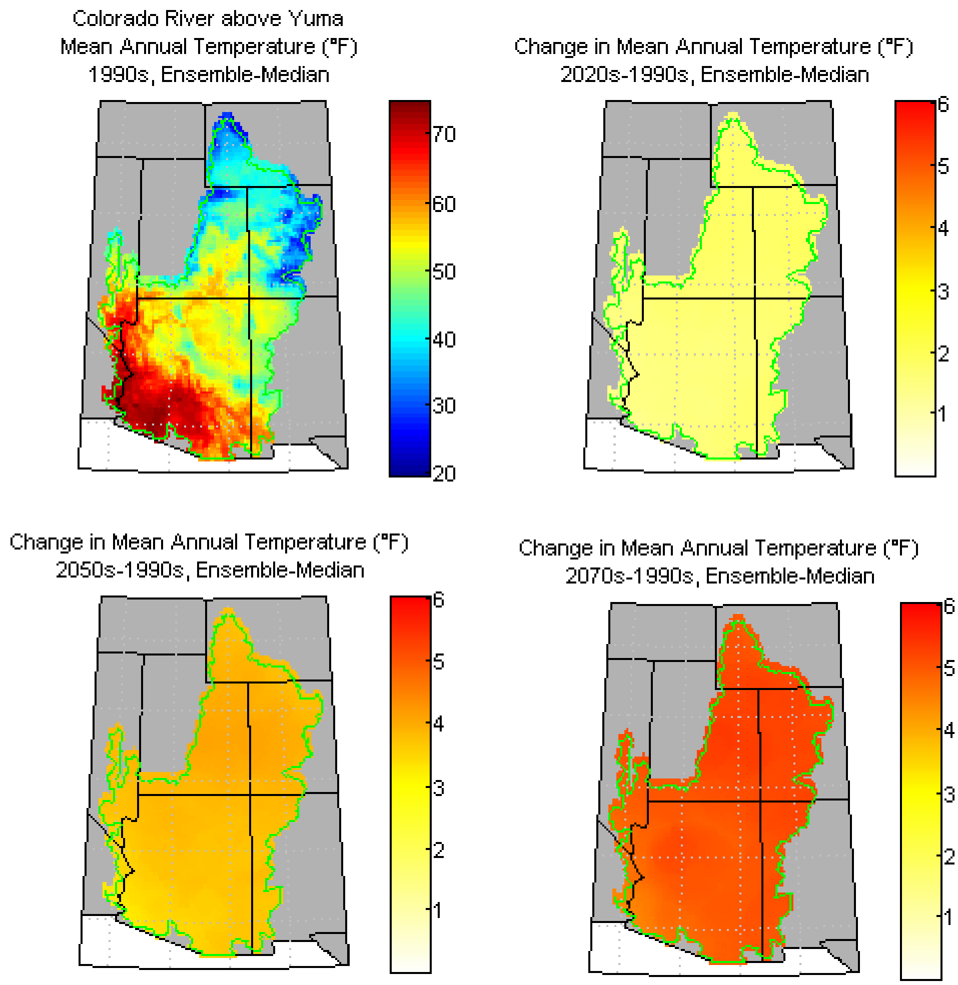


Figure 8. Simulated decade-mean temperature over the Colorado River Basin above Yuma, Arizona.

Figure 8 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.004 inch and are not considered in the change assessment.

Warmer temperatures are observed in lower lying areas of the Upper and Lower Colorado River Basins, particularly along the Colorado River mainstem and towards the south. Likewise, the Upper Colorado River Basin precipitation is generally greater in the north and also at a higher elevation (figure 9, top left panel). As related to climate change, temperature changes are generally uniform over the basin, and steadily increasing through time (figure 8). For Upper Colorado River Basin precipitation, similar results are found (figure 9), although there is some minor spatial variation in projected changes. During the early 21st century (2020s), there was a small percentage increase in precipitation over much of the basin. By the middle to late 21st century, the middle to lower portions of the basin are projected to experince a decrease while there's a continuing trend toward wetter conditions expected in the northern portion. The apparent change from an increase to a decrease in precipitation in the 2020s to decreases to the 2050s and 2070s may be an artifact of the analysis methodology. For example, this analysis focuses on decade-windows (consistent with other basin chapters in this report) rather than multidecade windows. The latter is featured in Reclamation (2011b), which uses a base period of climate model simulated 1950–1979 and then measures climate change using moving 30-year windows relative to this base period. From this perspective, the consensus change in 30-year mean precipitation is drier, but there's still a "no change" phase during the early 21st century using this view. Another explanation could be artifacts of generating climate simulations or downscaling (Reclamation 2011a). Such uncertainties require further investigation.

As climate changes in the 21st century, hydrology is expected to be affected in various ways, including snowpack development. As noted previously, increased warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify this impact on snowpack, it is apparent that warming trends in the Upper Basin tend to dominate expected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 10). Decreases in snowpack are expected to be more substantial over the lower-elevation interior portion of the Upper Colorado Basin where baseline cool season temperatures generally are closer to freezing thresholds and more sensitive to projected warming.

Changes near the mountainous rim of the Upper Colorado Basin, particularly along the northern and eastern rims, are expected to be small to minimal, generally because baseline temperatures at these locations are cool enough to absorb projected warming without much loss of snowpack.

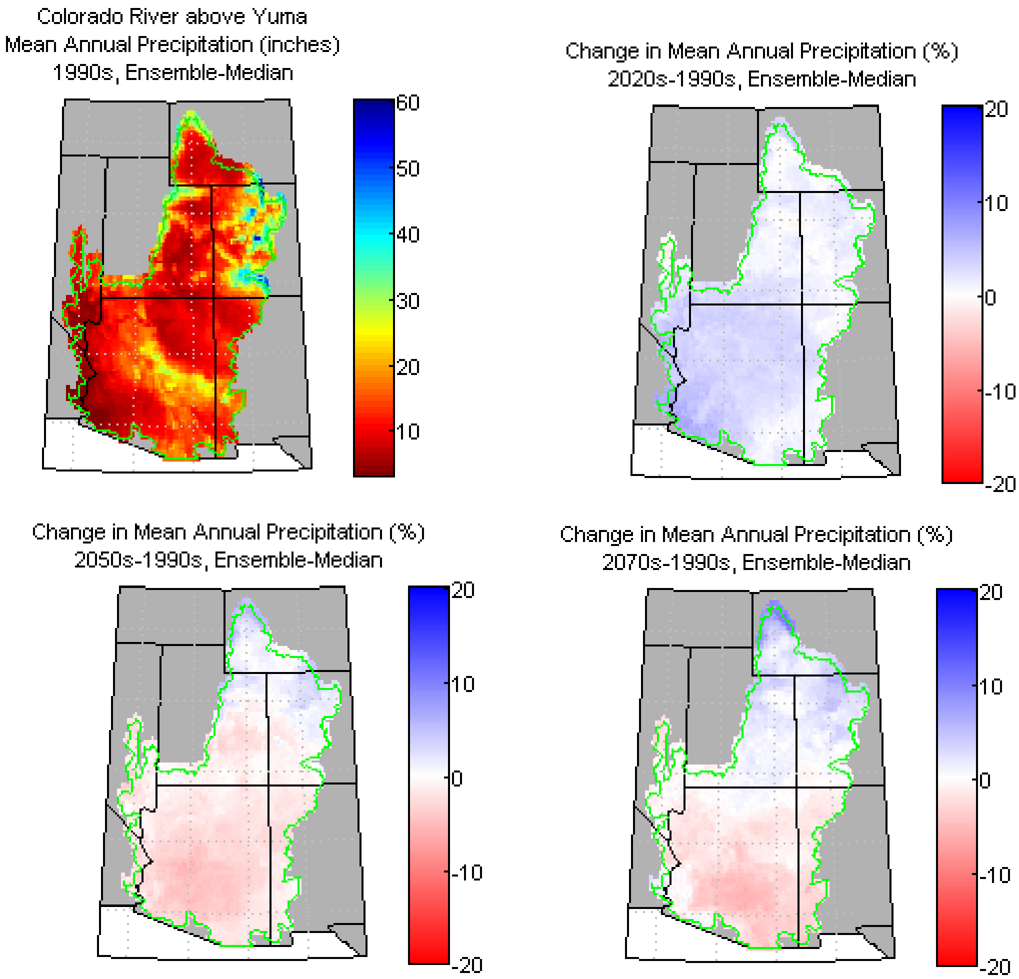


Figure 9. Simulated decade-mean precipitation over the Colorado River Basin above Yuma, Arizona.

Figure 9 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than a 0.004 inch and are not considered in the change assessment.

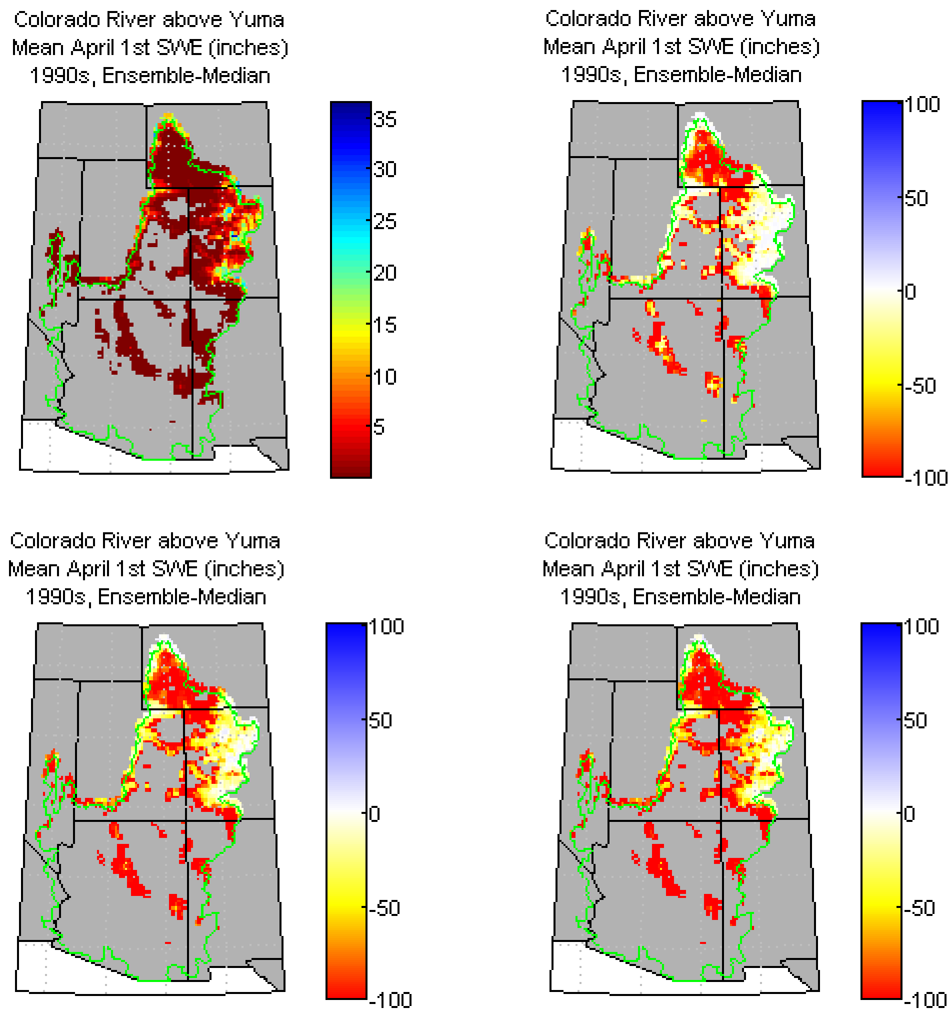


Figure 10. Simulated decade-mean April 1^{st} snowpack over the Colorado River Basin above Yuma, Arizona.

Figure 10 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.004 inch and are not considered in the change assessment.

As the effects of climate change and snowpack are realized throughout the Colorado River Basin, these effects will drive changes in the availability of natural water supplies. These effects may occur as changes to annual runoff and changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would serve to offset or amplify this impact. Results from Reclamation (2011a) suggest that annual runoff effects vary by location in the Colorado River Basin (figure 11), depending on baseline climate and the projected temperature and precipitation changes. For example, annual runoff from the Green River basin is expected to change relatively less than other subbasins. This is because the Green River basin is expected to experience warming with modest precipitation increases. In contrast, southern subbasins are expected to experience increased warming, and precipitation is expected to experience little change or decrease. Hence, greater decreases in annual runoff are expected for southern subbasins. On progression of change through the three future decades, it's notable that changes in annual runoff are minor during the 2020s relative to 2050s and 2070s. This finding relates to the progression of projected precipitation changes through these decades, as shown on figure 9 (i.e., where precipitation changes during the 2020s are slightly wetter for the middle to lower basin before transitioning to generally drier by 2050s and 2070s).

The seasonality of runoff is also projected to change. Warming is expected to lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This logically leads to increases in December–March runoff and decreases in April–July runoff. However, results show that seasonal runoff changes vary by subbasin (figure 11) and appear to be affected by factors other than annual warming (e.g., baseline climate, seasonal aspects of precipitation change). For example, even with projected levels of warming, December–March runoff in the Green River subbasin is projected to decrease while April–July runoff may increase (the latter reflecting projected snowpack increases along the northern mountainous rim, figure 10). By comparison, the Gunnison River subbasin is projected to experience April–July runoff decreases, suggesting that the balance of warming and cool season precipitation change, overlaid on baseline climate conditions, leads to less spring snowpack and reduced spring snowmelt. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller addresses how higher elevation snowpack contributes proportionally more to April–July

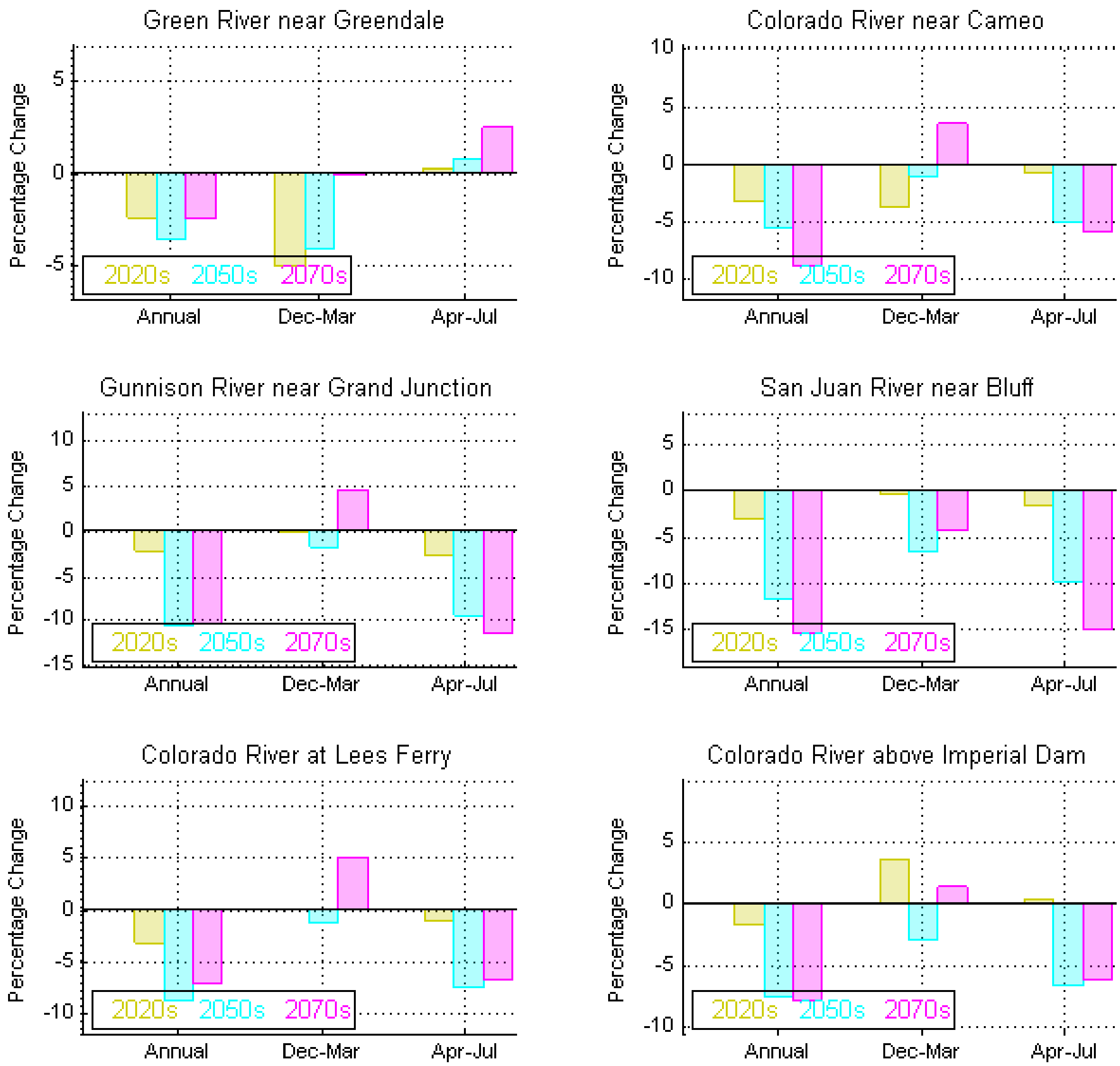


Figure 11. Simulated changes in decade-mean runoff for several subbasins in the Colorado River Basin.

Figure 11 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to runoff events relevant to flood control and ecosystem management is also of interest, although there is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Changes in flood-related events may be relevant to the management of various Colorado River Basin reservoirs, particularly along Upper Colorado River Basin tributaries. Likewise, changes in low-flow events may be relevant to a host of water and ecosystem management objectives situtated at basin reservoirs. Generally speaking, streamflow variability over the Upper Colorado River Basin is expected to continue under changing climate conditions. Utilizing annual maximum- and minimum-week runoff as metrics for flood-related and low-flow events, respectively, (figure 12) of projections suggests annual maximum-week runoff to remain relatively stable or decline slightly thoughout the Colorado River Basin. Annual minimum-week runoff may steadily decrease. It should be noted that a considerable amount of uncertainty is associated with projections at a submonthly scale because they are derived from projections from models calibrated at monthly time steps. More detailed and location-specific analysis is needed to make quantitative assessments with respect to the potential changes in flood-related and low-flow events at submonthly time steps.,

A summary of climate and hydrologic changes is provided in table 1 for three subbasins of the Colorado River Basin: Green River at Greendale, Colorado River at Lees Ferry, and Colorado River at Imperial Dam. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

2.4.2 Other Studies of Future Climate and Hydrology

The findings from Reclamation (2011a) are generally consistent with other studies on future climate and hydrology within the Colorado River Basin, particularly in terms of suggesting future decline in annual runoff and future shifts in runoff seasonality. However, other studies have been conducted using a variety of climate change assumptions and analytical techniques, leading to different projected levels of impact. These studies include: Revelle and Waggoner (1983), Nash and Gleick (1991 and 1993), Christensen et al. (2004), Milly et al. (2005), Hoerling and Eischeid (2007), and Christensen and Lettenmaier (2007). For example, reported estimates of potential decreases in Upper Colorado River Basin runoff at Lees Ferry inflows range broadly (6–45% reductions in mean annual runoff). These studies were reviewed in Reclamation (2007), and the authors of that report offered some conclusions that put this projected runoff uncertainty into context. A systematic comparison of these studies (Hoerling et al. 2009) yields some interesting insights into hydrology models, input data, and likely levels of Colorado River runoff decline. First, Hoerling and Eischeid (2007) now believe that their estimate of 45% runoff reduction overstates potential Colorado River losses. Using different, but equally valid methods, VIC model projections of future runoff changed from a 5% reduction by 2050 (Christensen and Lettenmaier 2007) to a 10% reduction.

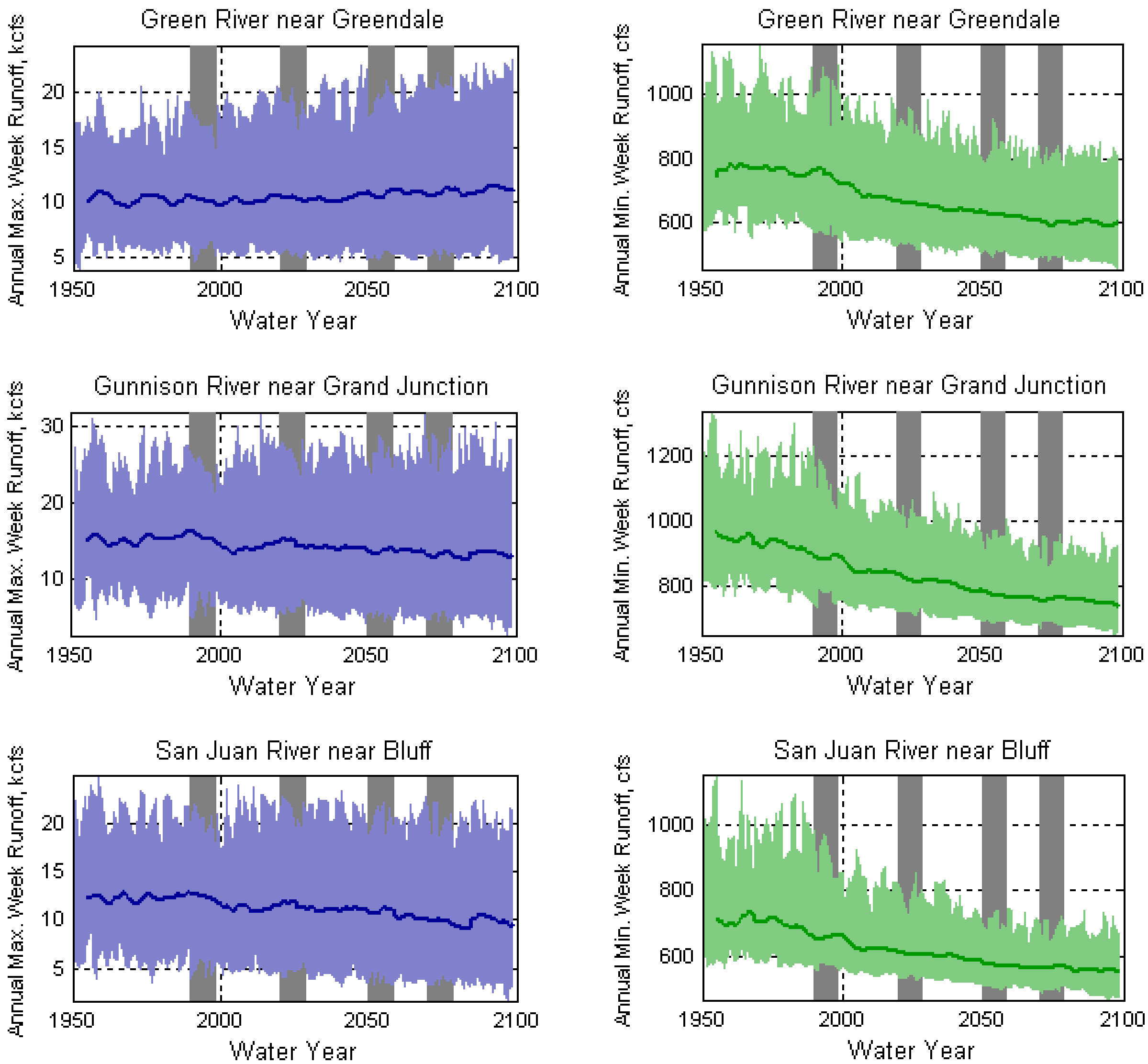


Figure 12. Simulated annual maximum and minimum week runoff for several subbasins in the Colorado River Basin.

Figure 12 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

Table 1. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Colorado River Basin

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Green River near Greendale			
Mean Annual Temperature (°F)	1.8	3.8	5.2
Mean Annual Precipitation (%)	0.7	2.1	3.6
Mean April 1st Snow Water Equivalent (%)	-46.5	-54.2	-58.9
Mean Annual Runoff (%)	-2.3	-3.5	-2.4
Mean December–March Runoff (%)	-4.9	-4.0	-0.1
Mean April–July Runoff (%)	0.3	0.7	2.4
Mean Annual Maximum Week Runoff (%)	1.9	6.2	7.7
Mean Annual Minimum Week Runoff (%)	-12.0	-16.6	-20.2
Colorado River at Lees Ferry			
Mean Annual Temperature (°F)	1.8	3.8	5.2
Mean Annual Precipitation (%)	-0.6	-0.3	-0.1
Mean April 1st Snow Water Equivalent (%)	-50.0	-60.6	-66.9
Mean Annual Runoff (%)	-3.1	-8.5	-6.9
Mean December–March Runoff (%)	0.1	-1.1	4.9
Mean April–July Runoff (%)	-1.0	-7.4	-6.5
Mean Annual Maximum Week Runoff (%)	-2.8	-3.5	-8.0
Mean Annual Minimum Week Runoff (%)	-8.2	-13.0	-14.9
Colorado River above Imperial Dam			
Mean Annual Temperature (°F)	1.8	3.7	5.1
Mean Annual Precipitation (%)	-0.4	-1.6	-0.7
Mean April 1st Snow Water Equivalent (%)	-58.5	-69.4	-74.6
Mean Annual Runoff (%)	-1.7	-7.4	-7.7
Mean December–March Runoff (%)	3.5	-3.0	1.3
Mean April–July Runoff (%)	0.3	-6.6	-6.1
Mean Annual Maximum Week Runoff (%)	-3.0	-3.7	-8.3
Mean Annual Minimum Week Runoff (%)	-7.9	-12.3	-14.0

A key difference between hydrology models used in Colorado River runoff projections is the runoff sensitivity to temperature changes. Hoerling et al. (2010) found that sensitivity ranged from 2–9% runoff reduction per °C (1.8 °F) increase in temperature—which implies a large range of runoff reductions, 4–18% by 2050. Based on their assessment of these and other factors, Hoerling et al. 2009 estimate that the Colorado River flow may decline 5–20% by 2050.

One aspect of the analysis that has been treated differently among studies is how GCM results are spatially downscaled from coarser GCM resolution to more local and basin-relevant resolution. The coarse spatial resolution of climate models limits their ability to represent topographic effects related to snowfall, snowpack evolution, and regional precipitation patterns (Grotch and MacCracken 1991; Giorgi and Mearns 1991; Pan et al. 2004; Reclamation 2007). Downscaling techniques may be used to recover some of this spatial detail. Summer precipitation associated with the North American monsoon is poorly simulated in most climate models (Lin et al. 2008; Gutzler et al. 2005). Using downscaled climate data, some of this may be improved, and there are some indications that winter precipitation in the mountainous areas of the Upper Colorado River Basin may increase (Christensen and Lettenmaier 2007). The results of Reclamation (2011a) are founded on spatial downscaling using a relatively simple technique where changes from GCMs are spatially disaggregated to local changes. In contrast, some studies have accomplished downscaling using relatively sophisticated techniques, featuring using a high-resolution climate models nested within a GCM's model domain over a region of interest (e.g., Rauscher et al. 2008). When this downscaling approach has been used to support the study of future changes in snowmelt-driven runoff in Western United States basins, the nature of effects have been generally the same as those discussed from Reclamation (2011a). However, the magnitude of change has differed, suggesting that the mode of downscaling does influence results.

2.5 Future Implications for Water and Environmental Resources

2.5.1 Water Supply, Reservoir Operations and Flood Management

Based on current reservoir operational constraints (e.g., storage capacity, flood control rules, constraints on reservoir water releases to satisfy various obligations), it appears that projected reductions in natural runoff and changes in runoff seasonality would lead to reduced water supplies under current system and operating conditions. This follows the understanding that storage opportunities during winter runoff season currently are limited by flood control considerations at several tributary reservoirs in the Colorado River Basin and that increased winter runoff under climate change will not necessarily translate into increased storage of water leading into the spring season. Capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during the spring and early summer season likely would translate into reductions in storage capture and likewise reductions in water supply for warm season delivery.

In Colorado River Basin reservoir systems with flood control objectives in currently snowmelt-dominated basins, warming without precipitation change could result in increased winter runoff volumes to manage during flood control operations. This could motivate adjustments to flood control strategies (e.g., Brekke et al. 2009 and Lee et al. 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to modify infrastructure to preserve flood protection performance and/or make flood control rule adjustments as climate changes (e.g., deeper winter draft requirements), which may further affect warm season water supplies (e.g., spring refill beginning with less winter carryover storage). More analysis is required to identify the spectrum of seasonal to acute runoff events relevant to current flood control operations, how these runoff events may change during the 21st century, and how current operating procedures may or may not be challenged in managing such future events. A framework for estimating flood frequency in the context of climate projection information was applied (Raff et al. 2009) to several basins in the Western United States including the Gunnison River.

2.5.2 Hydropower

Electricity demand, from hydropower generation and other sources, generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007).

Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production. In the Upper Colorado River Basin, major fluctuations in power generation vary seasonally to annually, depending on the reservoir system being considered. Thus, for some tributary systems, changes in seasonal runoff patterns might be more significant; while for others, changes in annual runoff might be more significant. In terms of demand, warming could lead to decreased energy demand during winter and increased demand during summer. In the Lower Colorado River Basin, power generation generally varies on an annual scale as annual runoff varies. This is due to the storage capacities of Lake Powell and Lake Mead being large enough to dampen fluctuations in monthly to seasonal inflows.

2.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with projected increases in air and water temperatures due to reduced flows and include increased stress on fisheries that are sensitive to a warming aquatic habitat. Warmer air and water temperatures could potentially improve habitat for quagga mussels and other invasive species that, in turn, may additionally impact maintenance of hydraulic structures. Other warming-related impacts include shifts in the geographic range of various species, impacts on the arrival and departure of migratory bird species, amphibian population declines, and effects on pests and pathogens in ecosystems.

2.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

2.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger increased reliance on ground water resources.

However, warmer, wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

2.5.6 Water Demands

Potential climate change impacts on agricultural, municipal and industrial, and instream water demands are difficult to predict; and existing information on the subject is limited. It is widely accepted that water demand changes will occur due to increased air temperatures, increased greenhouse gas concentrations, and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Furthermore, these natural impacts under climate change must be considered in combination with socioeconomic forces including future changes in infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Agricultural irrigation is the predominant water demand in the Colorado River Basin as well as the greater Western United States (Frederick 1997). Given that the atmosphere's moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, it is understood that crop water needs to respond to not only temperature and precipitation conditions but also atmospheric carbon dioxide, ozone, and potential evapotranspiration (e.g., Baldocchi and Wong 2006; Bloom 2010), with the latter affected by solar radiation, humidity, and wind speed. The uncertainties in projecting climate changes on carbon dioxide, ozone, and potential evapotranspiration leads to uncertainties in projecting future irrigation demands.

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Other consumptive uses associated with agricultural reservoir systems management include reservoir evaporation and losses during water conveyance and onfarm application. These types of system losses can be significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

Through the scenario planning process being undertaken by the Colorado River Basin Study, an in-depth assessment of plausible future water demands, including changes due to a changing climate, will be performed.

3. Basin Report: Columbia

3.1 Basin Setting

The Columbia River Basin is in the Pacific Northwest region of the United States extending over and encompassing seven states in the United States and parts of southern British Columbia, Canada (figure 13). The Columbia River is the largest river in the Pacific Northwest at over 1,240 miles long and drains roughly 260,000 square miles, 15% of which is within Canada. The Columbia River headwaters are within the Rocky Mountains in British Columbia. The river flows northwest before heading south into the State of Washington and continues westerly forming the boundary between Oregon and Washington before it drains into the Pacific Ocean. The Columbia River has an annual average runoff of approximately 200,000,000 acre-feet (275,000 cubic feet per second) with

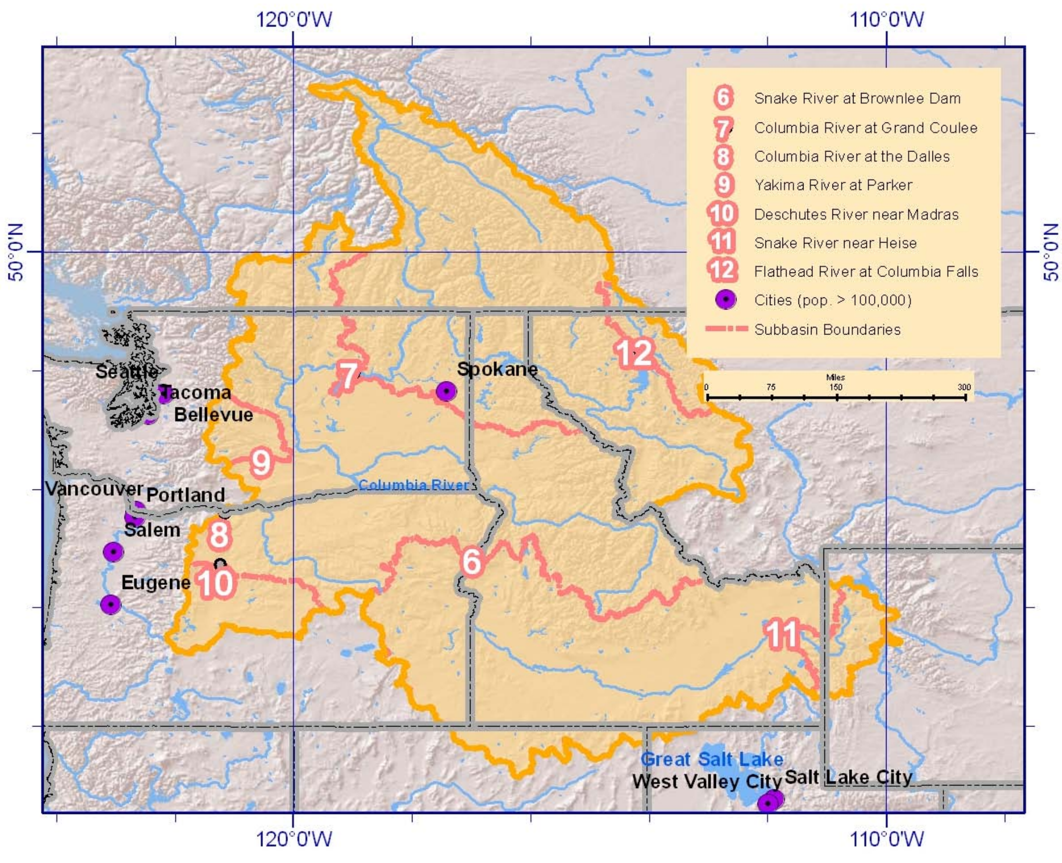


Figure 13. Columbia River Basin above The Dalles and runoff-reporting locations for this report.

roughly 25% of that flow contributed by the Canadian portion of the basin (USACE 1989). The boundary with the Pacific Ocean creates saltwater intrusion to approximately 23 river miles upstream of the mouth, and tidal effects can be experienced to Bonneville Dam, located 146 river miles inland.

The Columbia River Hydropower System includes both Federal and non-Federal production accounts for nearly 80% of the energy development in the Pacific Northwest. The Columbia River system water management system supplies water from 54 reservoirs that have a total active capacity of over 18 million acre-feet. Major tributaries to the Columbia River include the Snake River (largest tributary to the Columbia River with a drainage area of 108,000 square miles); the Yakima River (Washington); the Kootenai, Clark Fork, and Flathead Rivers originating in Montana; and the Willamette, Klamath, and Cowlitz Rivers in Oregon. Key locations referred to in this report are shown on figure 13, including the Columbia River at The Dalles, the Snake River at Brownlee Dam, Yakima River at Parker, Deschutes River near Madras, and the Flathead River at Columbia Falls (USACE 1989).

Reclamation collaborates with other Federal agencies, with the water resource departments for Oregon, Montana, and Idaho, the State of Washington's Department of Ecology, Native American tribes, local entities, and water users on a variety of water resource planning activities, which include water supply analysis, water quality assessments, renewable energy, and water conservation activities. A couple of examples of this collaboration are the River Management Joint Operating Committee (RMJOC), the Columbia Basin Development League, and the Columbia River Water Resources Program Policy Advisory Group. The RMJOC is comprised of Bonneville Power Administration, U.S. Army Corps of Engineers, and Reclamation to coordinate activities on river management within the Columbia River Basin. With respect to climate change, Reclamation is working with the RMJOC to develop a coordinated set of climate change projections to support long-range planning in the Columbia River Basin, by both Federal agencies as well as States, tribes, local governments, and nonprofits.

Reclamation coordinates with the Columbia Basin Development League, which is a 501 C-6 nonprofit organization incorporated in 1964 with the mission to provide support for the Columbia Basin Irrigation Project and its future development, protect its water rights, and educate the public on renewable resource and multipurpose benefits of the project. Reclamation also coordinates with the Columbia River Water Resources Program Policy Advisory Group, which was formed in 2006. The group creates a forum for the State of Washington's Department of Ecology to talk with stakeholders about key Columbia River water resource management issues and for stakeholders to build understanding of one another's perspectives and identify areas of common interest.

Climate varies considerably over the Columbia River Basin, both from year-to-year and geographically. The year-to-year variability is driven by the El Niño/Southern Oscillation (ENSO), which has a strong influence on the Columbia River Basin causing dryer conditions in the basin, typically on a 4-year cycle. Geographically, the Columbia River Basin climate is influenced by the north-south Cascade Mountain Range and the Blue-Wallowa Mountains of northeast Oregon. The climate within the basin generally varies from cooler and wetter on the western "windward" side of these ranges to warmer and drier on the eastern "leeward" side (Oregon Climate Research Institute [OCCRI] 2010).

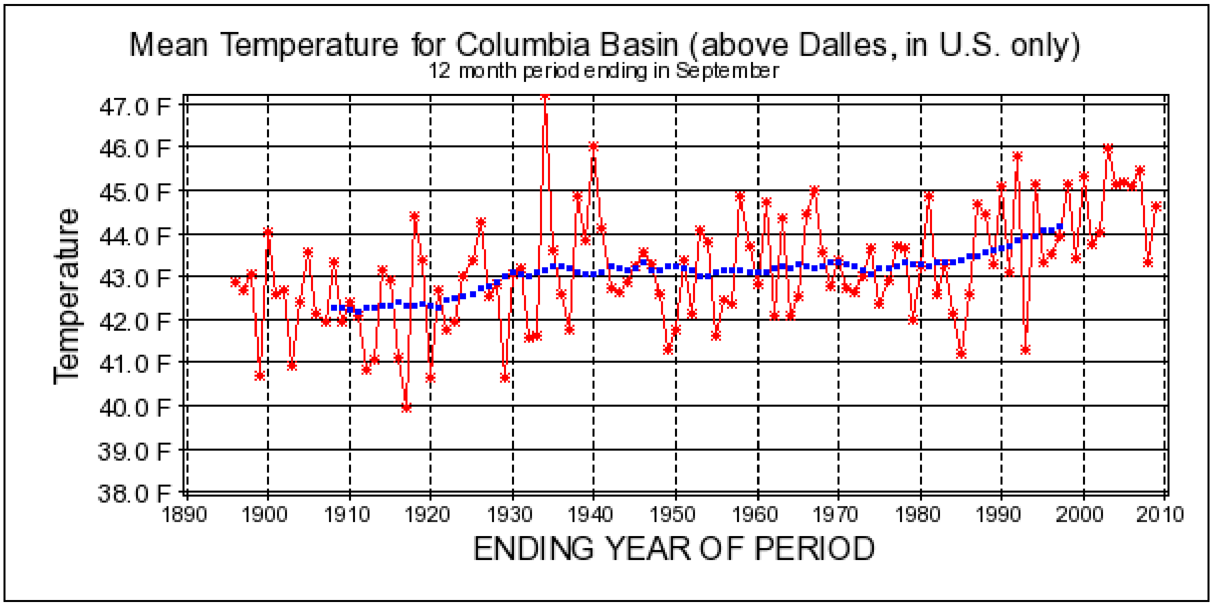
3.2 Historical Climate

Over the course of the 20th century, warming has been prevalent over the Columbia River Basin (figure 14). The basin's average mean-annual temperature has increased by approximately 2 °F since the late 1800s. However, throughout much of this period, large variations in annual temperature have been recorded.

Warming within the basin has not occurred steadily throughout the 20st century. As depicted within figure 14 (top panel), the basin average temperature increased from the late 1800s to the 1930s; but then from the 1930s to the 1980s, it generally remained unchanged. However, since the 1980s, basin average temperatures again have been steadily increasing.

Basin average annual precipitation, depicted within figure 14 (bottom panel), ranges between 20 to 25 inches. No apparent trend in precipitation over the period of record exists. A small decrease in precipitation occurred in the early 1900s; but since the middle of the 20th century, total precipitation generally has remained unchanged. Unlike temperature, annual precipitation variability has been minor from year to year until recently when temperature variation appears to have increased.

Other analyses have shown trends toward increasing winter precipitation during 1950–1999 at many Western United States sites, including several in the Pacific Northwest (Regonda et al. 2005); however, a consistent region-wide trend is not apparent over this period. The former U.S. Climate Change Science Program issued the Synthesis and Assessment Product 3.3 (SAP 3.3) (CCSP 2008), which reports that heavy precipitation events averaged over North America have increased over the past 50 years (Gutowski et al. 2008). An analysis of extreme precipitation events was presented by Kunkel (2003) that indicated there has been



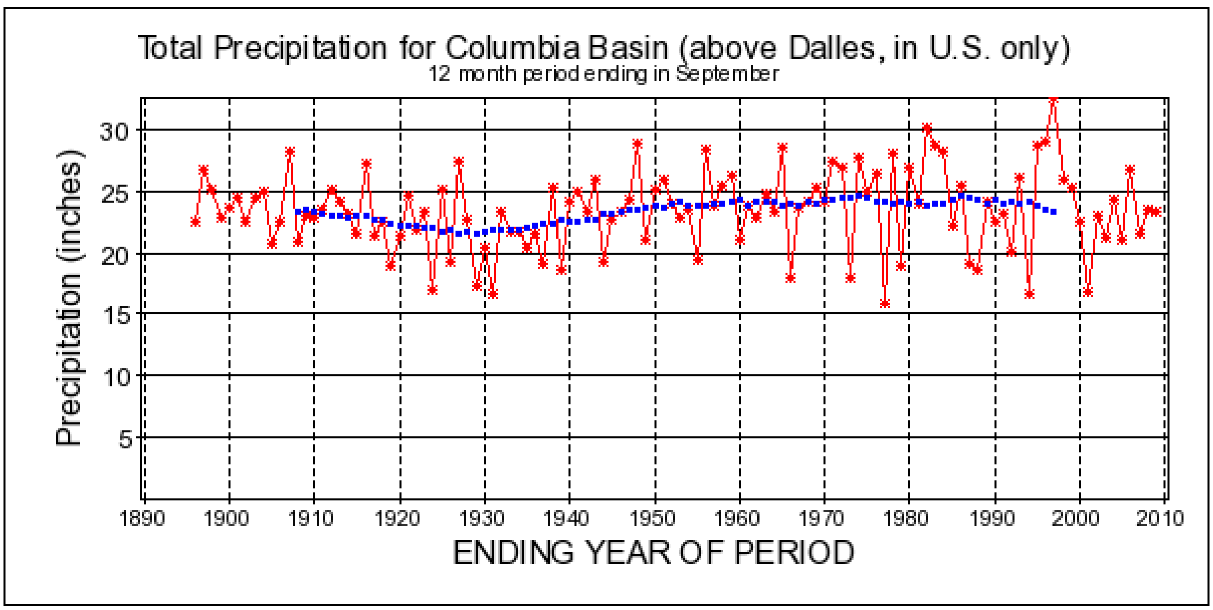


Figure 14. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Columbia River Basin above The Dalles.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

an increase in the frequency of such events since the 1920s/1930s in the United States. Trends in extreme precipitation events also were evaluated between 1948–2006 for each State using the method of Kunkel et al. (1998), and similar findings were reported by Madsen and Figdor (2007).

3.3 Historical Hydrology

Runoff within the Columbia River Basin has varied considerably from year-to-year. Runoff also varies geographically; during any particular year, some portions of the basin may experience relatively greater runoff while others areas experience relatively less runoff. A review of historical information in the Columbia River Basin indicates that runoff trends within the basin may exist depending on the location and historical period that is assessed. However, evaluation of these trends suggests that statistically they are relatively weak to insignificant.

Coincident with the climate trends discussed in the previous section, the Western United States and Columbia River Basin also have experienced a general decline in spring snowpack, reduction in the amount of precipitation falling as snow in the winter, and earlier snowmelt runoff between the mid- and late-20th century (Knowles et al. 2007; Regonda et al. 2005). Several studies suggest that many observed trends for SWE, soil moisture, and runoff in the Western United States are the result of increasing temperatures rather than changes in precipitation (Lettenmaier et al. 2008). There also may be a trend towards reduced annual streamflow during dry years (Luce and Holden 2009). Annual peak discharge records indicate that, due to a number of factors, an assessment of whether observed changes are due to natural climate variability or climate change is not possible (Villarini et al. 2009)

The changes discussed in the previous paragraphs over regional drainages such as the Columbia River Basin are sensitive to the uncertainties of station measurements as well as the period of analysis and location being analyzed. For the entire Western United States, observed trends of temperature, precipitation, snowpack, and streamflow might be partially explained by anthropogenic influences on climate (e.g., Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009); however, it remains difficult to attribute observed changes in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends in precipitation (Hoerling et al. 2010) and in basin-scale conditions rather than at the larger Western United States scale (Hidalgo et al. 2009). However, for the various drainage scales considered in Hidalgo et al. (2009) (i.e., Columbia River at the

Dalles (~680,000 square kilometers [km^2]), Colorado River at Lees Ferry (~280,000 km^2), Sacramento River at Bend Bridge (~32,000 km^2), and several basins smaller than 6,000 km^2), results for the largest drainage—the Columbia River Basin—suggested that some regional hydroclimate trends could be attributed to human influences on climate (Hidalgo et al. 2009).

3.4 Future Changes in Climate and Hydrology

While the previous section focused on historical conditions, this section summarizes results from studies focused on future climate and hydrologic conditions within the Columbia River Basin. Discussion first focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document. However, it is notable that, during the past several decades, many studies have been conducted on projected future hydroclimate of the Columbia River Basin, and a subsequent discussion is offered on the key findings and themes from these studies.

3.4.1 Projections of Future Climate and Hydrology

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the persepctive of basin-average and secondly as those climate conditions distributed throughout the basin. Discussion then segues to a summary of snow-related effects under future climate conditions as they may be distributed throughout the basin. Subsequently, a discussion is offered on how climate and snowpack changes translate into effects on annual and seasonal runoff, as well as acute runoff events relevant to flood control and ecosystems management.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation; they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Columbia River Basin may increase steadily during the 21st century (figure 15). Focusing on the Columbia River above The Dalles Dam, the basin-average mean-annual temperature is projected to increase by approximately 6–7 °F during the 21st century, with range

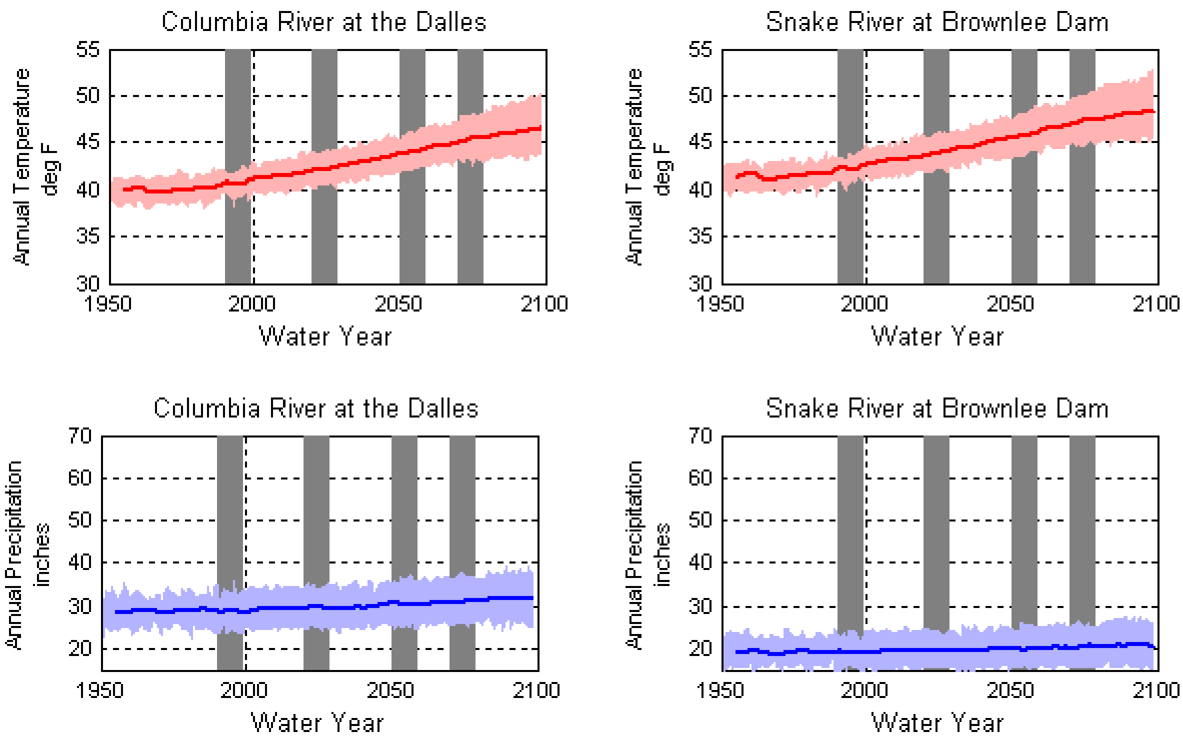


Figure 15. Simulated annual climate averaged over the Columbia River Basin and Snake River subbasin.

Figure 15 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

of annual possibility widening through time. A similar trend is founds for projected temperatures over the Snake River subbasin above Brownlee Dam.

The same climate projections suggest that mean-annual precipitation, averaged over the Columbia River Basin and the Snake River subbasin, is not expected to change significantly through the 21st century. This is evident by following the ensemble median of the annual precipitation through time for both basins, noting that the condition remains relatively static during the early 21st century and then slightly increases during the last half of the 21st century.

Some geographic complexities of climate change emerges over the Columbia River Basin when climate projections are inspected location by location, particularly for precipitation change. For example, consider the four decades highlighted with vertical gray bars on figure 15. They represent the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, temperatures are generally cooler in the north and along the mountainous rim (figure 16, top left panel). Warmer temperatures are observed in lower lying areas of the interior Columbia River Basin and throughout the Snake River plain of southern Idaho. Likewise, precipitation is generally greater in the north and at higher elevation (figure 17, top left panel). Addressing climate change, temperature changes are generally uniform over the basin and steadily increasing through time (figure 16). For precipitation, similar results are found (figure 17), with a trend toward wetter conditions throughout the basin. These trends generally are greater towards the northern portion of the basin.

As climate changes in the 21st century, hydrology is expected to be affected in various ways, including snowpack development. As noted previously, warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could offset somewhat or amplify this impact on snowpack, it is apparent that warming trends in the Columbia River Basin tend to dominate expected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 18). Decreases in snowpack are expected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. This is particularly the case for the Cascades Mountains along the western rim of the basin and the lower elevations of the Owyhee and Rocky Mountains to the East. These mountain ranges contribute significantly to runoff in headwater reaches of major Columbia River tributaries. Decrease snowpack volume also could result in decreased ground water infiltration, runoff, and ultimately decreased contribution to summer base flow in rivers. Contrary to these effects, it is notable that the northern and higher-elevation eastern portions of the basin are projected to experience net increases in April 1st snowpack, generally reflecting a trend toward increasing precipitation in these regions with baseline temperatures that are cool enough to experience the projected warming without loss of snowpack.

As the effects of climate change and snowpack are realized throughout the Columbia River Basin, these effects will drive changes in the availability of natural water supplies. These effects may be experienced in terms of changes to

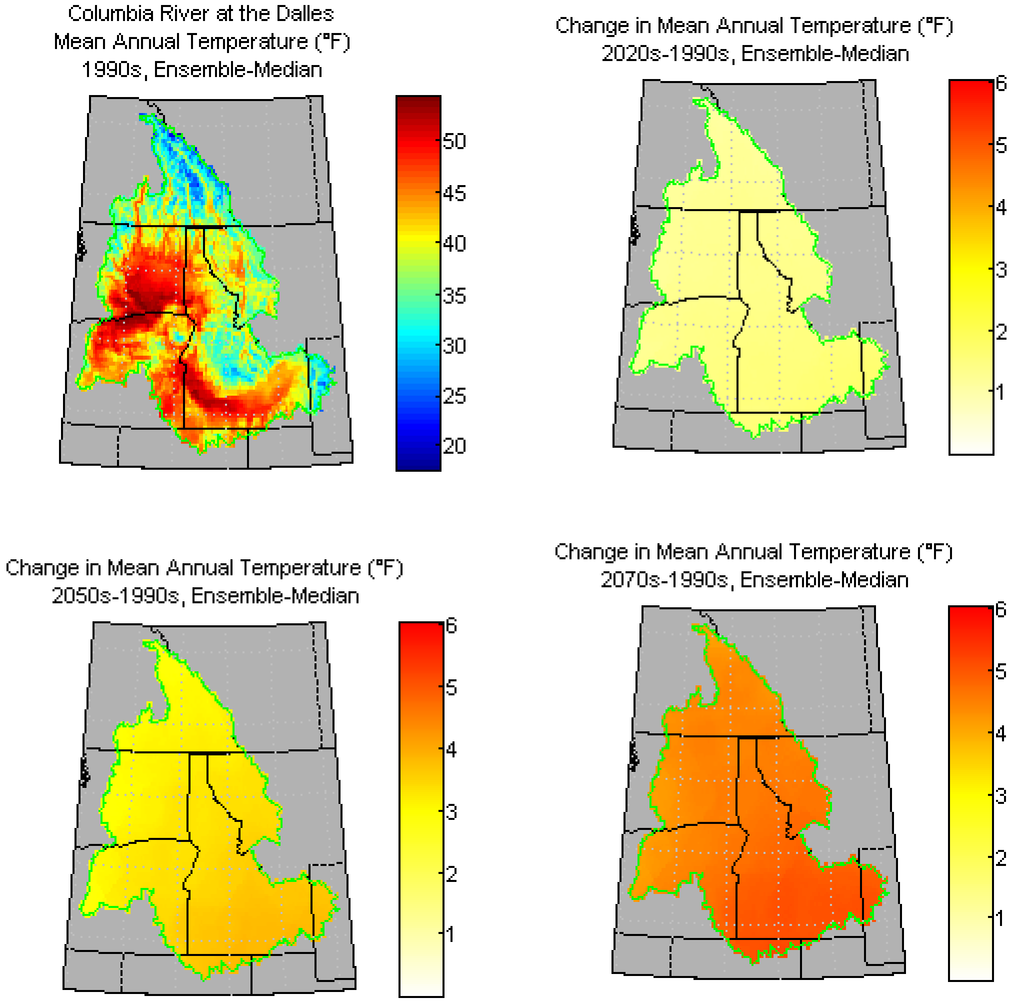


Figure 16. Simulated decade-mean temperature over the Columbia River Basin above The Dalles.

Figure 16 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s) and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

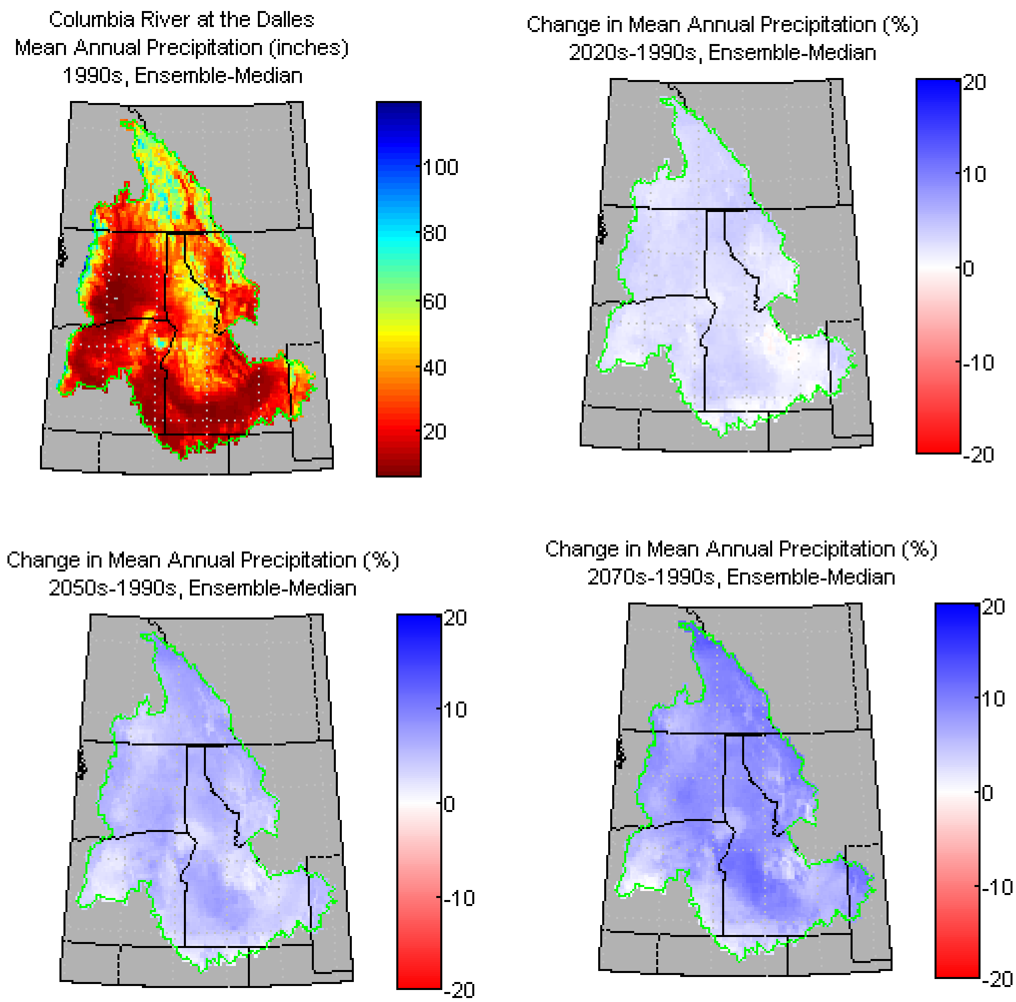


Figure 17. Simulated decade-mean precipitation over the Columbia River Basin above The Dalles.

Figure 17 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s) and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

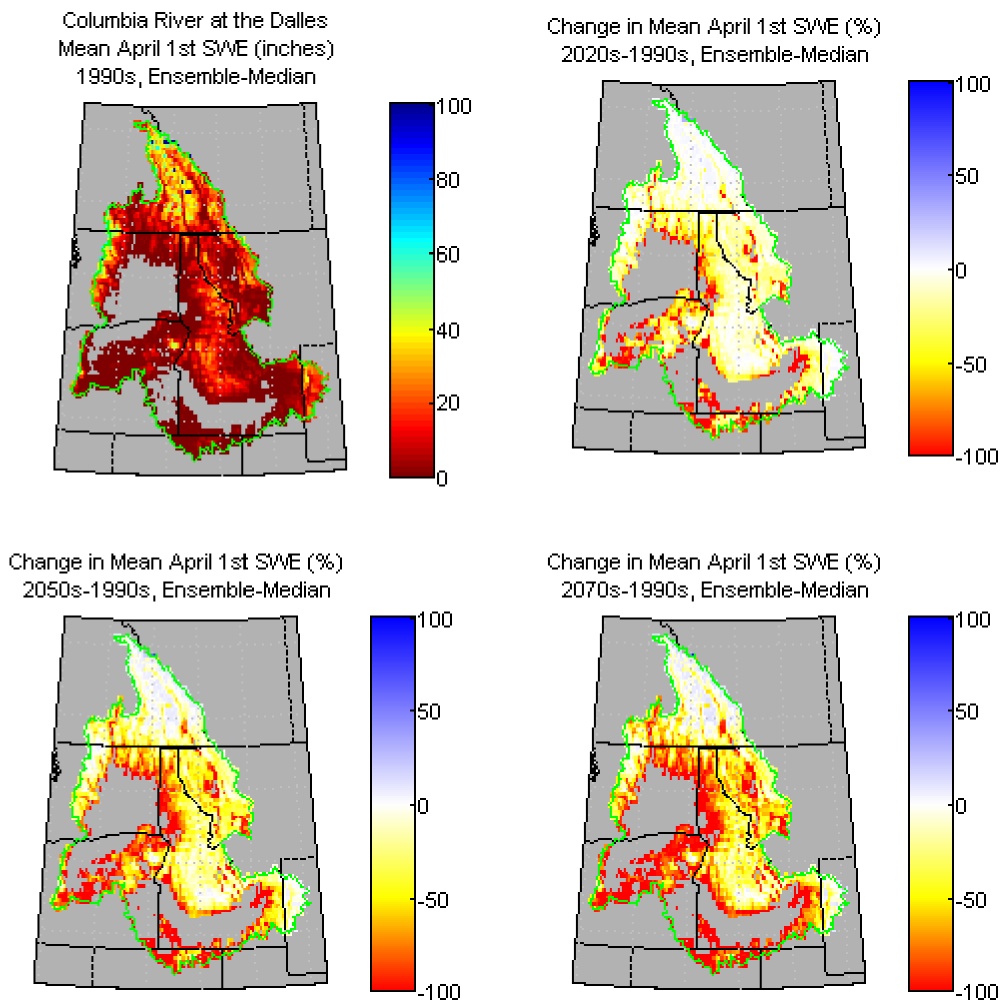


Figure 18. Simulated decade-mean April 1st snowpack over the Columbia River Basin above The Dalles.

Figure 18 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s) and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

annual runoff, and also changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would serve to offset or amplify this impact. Results from Reclamation (2011a) suggest that annual runoff effects vary by location in the Columbia River Basin (figure 19) depending on baseline climate and the projected temperature and precipitation changes. For example, changes in annual runoff from subbasins in the southern and central portions of the basin (e.g., Snake, Deschutes and Yakima River subbasins) are expected to be relatively less than changes in the northern subbasins. This is a reflection of how the southern and central subbasins are expected to experience less precipitation increase than northern subbasins (figure 17).

The seasonality of runoff is also projected to change. Warming is expected to lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This logically leads to increases in December–March runoff and decreases in April–July runoff. However, the degree to which these conceptual results bear out in the Columbia River Basin appears to vary by subbasin (figure 19). Focusing on December–March seasonal runoff, the concept generally holds as results show increased mean seasonal volume by the 2020s and a trend toward greater increases by the 2070s. Focusing on April–July seasonal runoff, the concept holds less well for the Columbia River Basin, apparently due to precipitation increases offsetting warming effects. This is particularly the case for the more northern subbasins (e.g., Flathead River at Columbia Falls, Columbia River at Grand Coulee). For more southern and central subbasins (e.g., Snake and Yakima Rivers), there is generally little projected change in April–July runoff through the 2070s. This suggests that, although projected warming would serve to diminish April 1st snowpack, there is still apparently enough projected precipitation increase to offset this warming effect and sustain April–July runoff. An exception among the southern subbasins is the Deschutes, where warming appears to dominate enough to cause a decrease in April–July runoff similar to the pattern in the northern subbasins. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

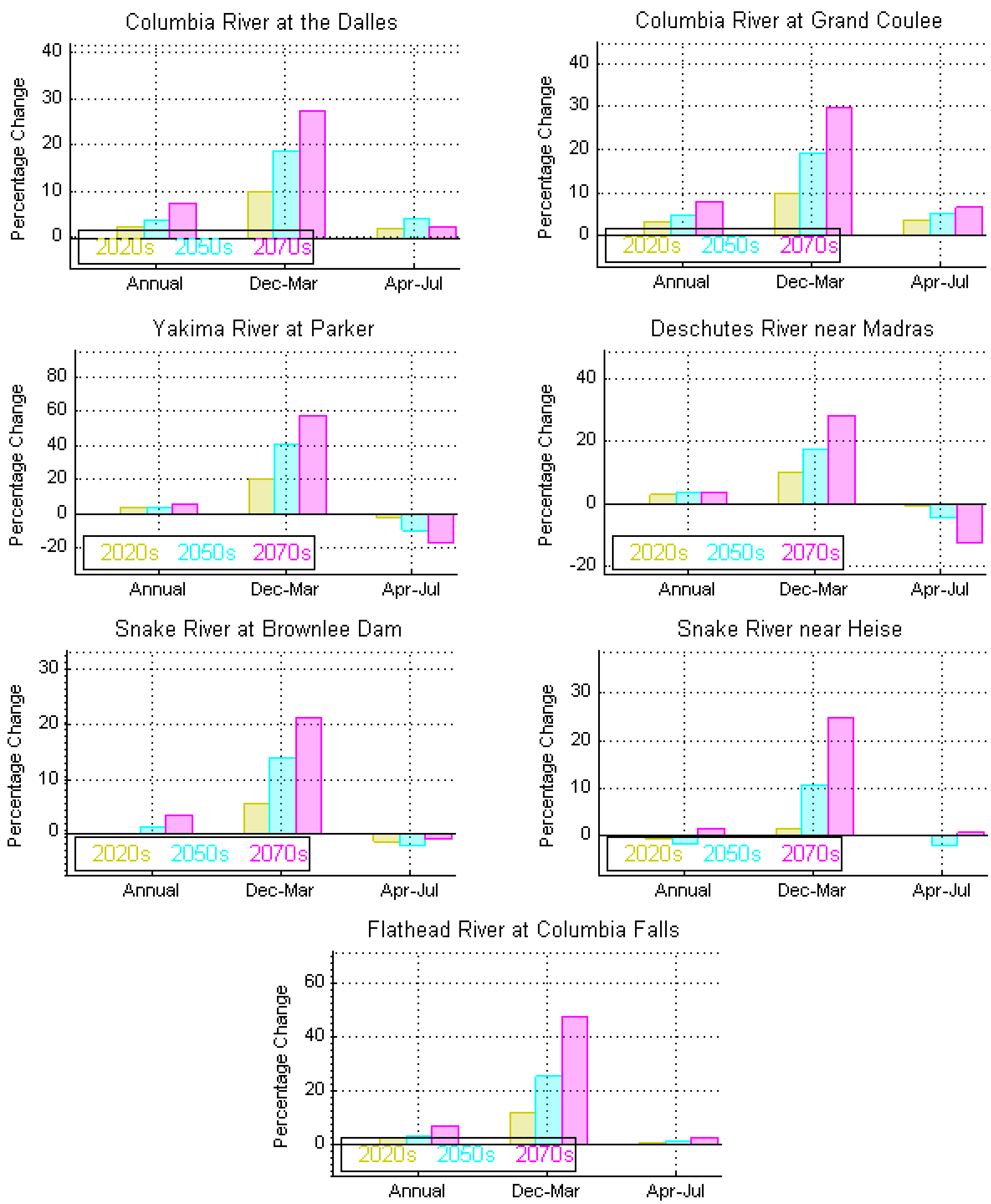


Figure 19. Simulated changes in decade-mean runoff for several subbasins in the Columbia River Basin.

Figure 19 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

Climate change in relation to runoff events relevant to flood control and ecosystem management is also of interest, although there is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Changes in flood-related events are relevant to the management of various Columbia River Basin reservoirs. Likewise, changes in low-flow events are relevant to a host of water and ecosystem management objectives situtated at basin reservoirs. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. Utilizing annual maximum- and minimum-week runoff as metrics for flood-related and low-flow events, respectively (figure 20), projections suggest that annual maximum-week runoff would remain relatively stable for central and southern subbasins (e.g., Yakima and Snake River subbasins) or slightly increase for northern subbasins (reflected in results for shown for Columbia River at The Dalles, which blend Yakima, Snake and upper Columbia subbasin results). Annual minimum-week runoff is projected to steadily decrease. Lower instream flows and increased summer air temperatures may result in warmer channel flow and possibly significant impacts on aquatic species and those species dependent on them. However, to truly understand potential changes in flood-related and low-events, and implications of these changes for reservoir management, more indepth analyses are warranted.

A summary of climate and hydrologic changes is provided in table 2 for three subbasins of the Columbia River Basin: Columbia River at The Dalles, Snake River at Brownlee Dam, and Yakima River at Parker. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

3.4.2 Other Studies of Future Climate and Hydrology

The findings from Reclamation (2011a) generally are consistent with other studies on future climate and hydrology within the Columbia River Basin (e.g., Hamlet and Lettenmaier 1999; Mote et al. 2003; Mastin 2008; Elsner et al. 2010), particularly in terms of suggesting future decline in annual runoff and future shifts in runoff seasonality. However, these studies have been conducted using a variety of climate change assumptions and analytical techniques, leading to different projected levels of impact. For example, two recent studies address potential climate change at a State geographic scale and suggest increases in average annual Pacific Northwest temperature of 1.1–3.3 °F by the 2020s (2010–2039), 1.5–5.2 °F by the 2040s (2030–2059), and 2.8–9.7 °F by the 2080s (2070–2099), compared to 1970–1999 (Salathé et al. 2009; OCCRI 2010). These studies suggest projected changes in average annual precipitation are small (+1 to +2%)

but that some of their analyses project enhanced seasonal precipitation cycles with changes toward wetter autumns and winters and drier summers.

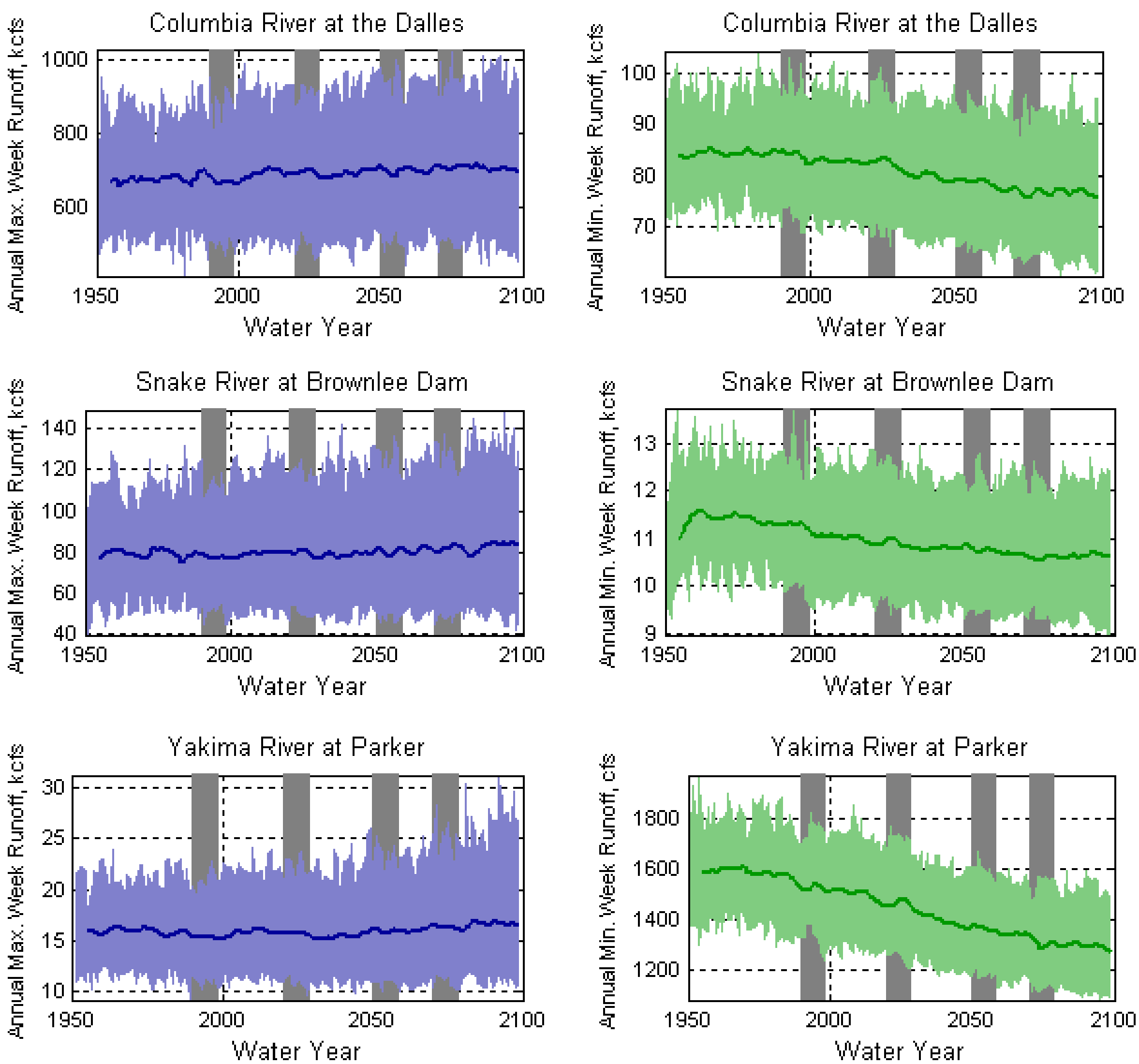


Figure 20. Simulated annual maximum and minimum week runoff for several subbasins in the Columbia River Basin.

Figure 20 displays the ensemble of annual "maximum 7-day" and "minimum 7-day" runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

Table 2. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Columbia River Basin.

Hydroclimate Metric (Change from 1990s)	2020s	2050s	2070s
Columbia River at The Dalles			
Mean Annual Temperature (°F)	1.4	3.2	4.6
Mean Annual Precipitation (%)	3.4	6.2	8.5
Mean April 1st Snow Water Equivalent (%)	-26.1	-39.3	-47.2
Mean Annual Runoff (%)	2.3	3.7	7.5
Mean December–March Runoff (%)	9.8	18.5	27.3
Mean April–July Runoff (%)	2.2	4.1	2.4
Mean Annual Maximum Week Runoff (%)	3.5	4.0	5.5
Mean Annual Minimum Week Runoff (%)	-1.5	-5.9	-8.5
Snake River at Brownlee Dam			
Mean Annual Temperature (°F)	1.6	3.6	5.0
Mean Annual Precipitation (%)	2.3	3.9	6.6
Mean April 1st Snow Water Equivalent (%)	-42.2	-57.6	-67.2
Mean Annual Runoff (%)	-0.1	1.2	3.4
Mean December–March Runoff (%)	5.6	13.7	21.0
Mean April–July Runoff (%)	-1.3	-2.0	-0.9
Mean Annual Maximum Week Runoff (%)	2.4	3.5	5.8
Mean Annual Minimum Week Runoff (%)	-3.0	-4.3	-5.9
Yakima River at Parker			
Mean Annual Temperature (°F)	1.3	2.9	4.2
Mean Annual Precipitation (%)	3.7	5.7	7.7
Mean April 1st Snow Water Equivalent (%)	-19.9	-37.6	-50.7
Mean Annual Runoff (%)	3.8	3.7	5.6
Mean December–March Runoff (%)	19.6	39.9	56.9
Mean April–July Runoff (%)	-2.0	-9.5	-17.0
Mean Annual Maximum Week Runoff (%)	2.7	4.2	6.7
Mean Annual Minimum Week Runoff (%)	-4.0	-10.6	-14.2

3.5 Future Implications for Water and Environmental Resources

3.5.1 Water Supply, Reservoir Operations and Flood Management

Based on current reservoir operational constraints (e.g., storage capacity, flood control rules, constraints on reservoir water releases to satisfy various obligations), it appears that projected effects on runoff seasonality from warming without precipitation change would lead to reduced water supplies under current system and operating conditions within the Columbia River Basin. This follows the understanding that storage opportunities during winter runoff season are currently limited by flood control considerations at basin reservoirs, and that increased winter runoff under climate change will not necessarily translate into increased storage of water leading into the spring season. Capture of snowmelt runoff has traditionally occurred during the late spring and early summer seasons. Reductions in runoff during the spring and early summer season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

In contrast, when future climate is adjusted to reflect projected warming with precipitation increase over the Columbia River Basin, the conceptual effects on reservoir operations are less obvious. Changes in precipitation can offset some of the warming effects on spring–summer runoff depicted in the previous section. However, the degree to this offset depends on future assumptions for temperature and precipitation, and several studies have featured a mix of assumptions where warming appears to be the most influential (e.g., Payne et al. 2004).

In Columbia River Basin snowmelt dominated reservoirs with flood control objectives, warming without precipitation change could result in increased winter runoff volumes to manage. This could motivate adjustments to flood control strategies (e.g., Brekke et al. 2009; Lee et al. 2009). For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff might suggest an increased flooding risk. If current flood protection values are to be preserved, it could become necessary to make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements) that may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage). More analysis is required to identify the spectrum of seasonal to acute runoff events relevant to current flood control operations, how these runoff events may change during the 21st century, and how current operating procedures may or may not be challenged in managing such future events.

3.5.2 Hydropower

Electricity demand, from hydropower generation and other sources, generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

For the Columbia River Basin, some studies have focused on how hydropower generation would be affected in the context of managing impacts to multiple reservoir operations objectives. Payne et al. (2004) reported that, under the future climate and hydrology scenarios considered in their study, there could be increased competition for maintaining reservoir storage in the interest of satisfying firm hydropower objectives versus drafting reservoir storage to satisfying instream flow targets developed pursuant to the Endangered Species Act listing of Columbia River salmonids. In a more recent study (Lee et al. 2009), a comparison of operations was conducted under existing and alternative operating criteria and under both 20th century climate and a future climate reflecting the 20th century climate warmed by 2 °C. Results showed that, under existing operating criteria, satisfaction of flood control objectives would be prioritized and lead to decreased storage trends and hydropower production. However, optimization techniques were used to show that, if adjustments to operating criteria were considered as an adaptation option, then it would seem possible to rebalance flood control and other system operating objectives so that many of the impacts to water supply and hydropower generation could be reduced while providing comparable levels of flood control to those produced by current flood control practices.

3.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change can also trigger synergistic effects in ecosystems and exacerbate invasive species problems.

On climate change implications specific to salmon fisheries in the Pacific Northwest, the Washington Climate Change Impacts Assessment (WACCIA) (Mantua et al. 2009) reports that rising stream temperatures likely will reduce the quality and extent of freshwater salmon habitat. WACCIA also suggests that the duration of periods that cause thermal stress and migration barriers to salmon is projected to at least double (low emissions scenario, B1) and perhaps quadruple (medium emissions scenario, A1B) by the 2080s for most analyzed streams and lakes; areas of greatest increases in thermal stress include the interior Columbia River Basin. These findings are consistent with other studies in the region (e.g., Battin et al. 2007).[6]

3.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

3.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on ground

[6] For additional discussion on climate change implications for Columbia River Basin salmon fisheries, see section "Climate Change and Ocean Conditions," pp. 37-62 of *Supplemental Consultation on Remand for Operation of the Federal Columbia River Power System, 11 Bureau of Reclamation Projects in the Columbia Basin and ESA Section 10(a)(I)(A) Permit for Juvenile Fish Transportation Program*," prepared by NOAA Fisheries, May 20, 2010).

water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

3.4.6 Water Demands

Potential climate changes on agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures, increased atmospheric carbon dioxide levels, and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these natural system changes must be considered in combination with socioeconomic changes including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Agricultural irrigation is the predominant water demand on Reclamation reservoir systems within the Columbia River Basin. Given that the atmosphere's moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, crop water demands respond to atmospheric carbon dioxide ozone and potential evapotranspiration in addition to temperature and precipitation (e.g., Baldocchi and Wong 2006; Bloom 2010). Additionally, agricultural water demand could decrease due to crop failures caused by changes in pests and diseases in the future. Seasonal volume of agricultural water demand could increase if growing seasons become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it may be more than 2 weeks longer than typical of the late 20th century (Gutowski et al. 2008). Another study suggests that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Potential instream water demand increases resulting from climate change within the Columbia River Basin could include ecosystem demands, hydropower and thermoelectric power production, industrial cooling, navigation, and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production also could be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on water allocations from year-to-year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographics, land use changes, and other nonclimate factors.

Other consumptive uses associated with agricultural reservoir systems management include reservoir evaporation and losses during water conveyance and onfarm application. These types of system losses can be significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

4. Basin Report: Klamath

4.1 Basin Setting

The Klamath River basin is located in a region that spans south-central Oregon to northwestern California (figure 21). The Klamath River originates in headwater streams of south-central Oregon, eventually flowing southwest, and picking up runoff from the Trinity River in California before reaching its coastal estuary. The Klamath Project (Project) is currently a single use Project located in south-central Oregon and north-central California. The Project supplies water to both agricultural and national wildlife refuge lands and provides flood control on the Klamath and Lost Rivers. Authorized for construction in 1905, the Project is one of the earliest Reclamation projects. The terrain within the upper basin varies from rugged, heavily timbered mountain slopes to rolling sagebrush benchlands and broad flat valleys. As the river descends into the lower basin, the terrain becomes primarily mountainous and more heavily timbered.

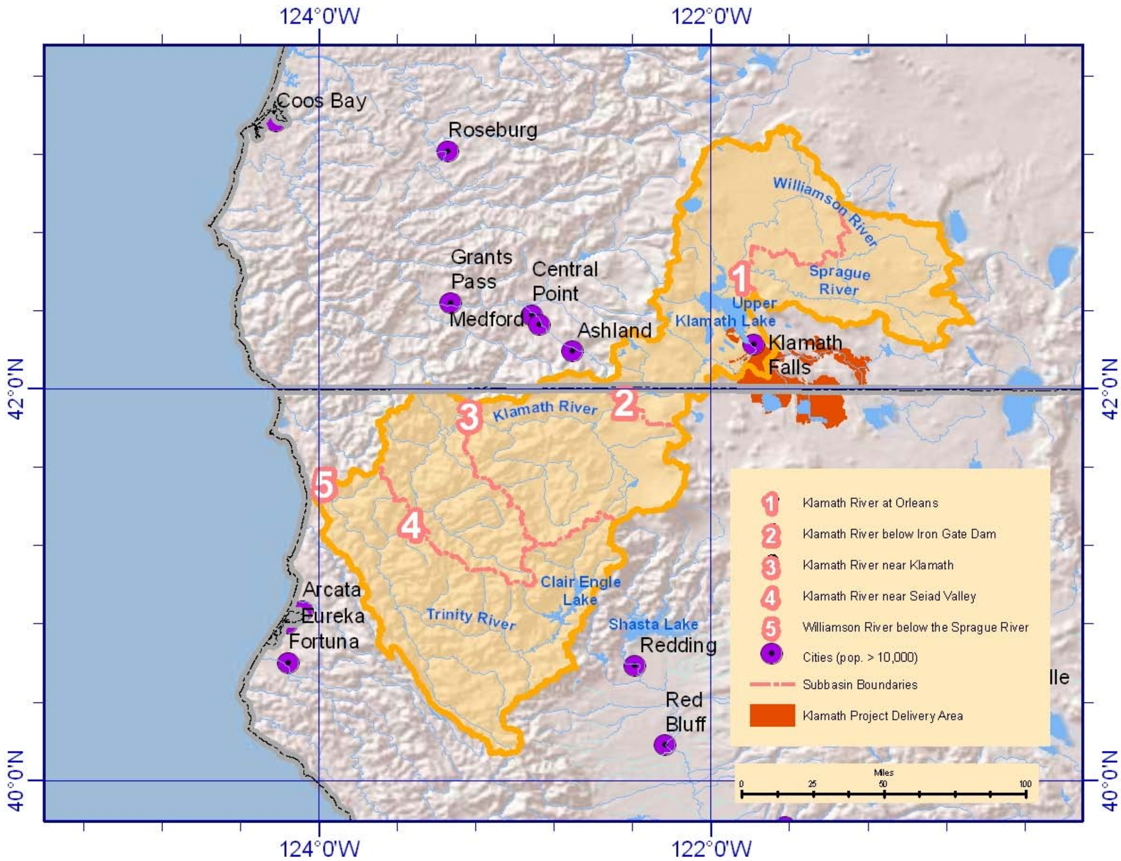


Figure 21. Klamath River basin and runoff-reporting Locations for this report.

Coordination within the basin includes Federal agencies, the States of California and Oregon, as well as the four Klamath basin tribes. Each year, the Natural Resource Conservation Service forecasts provide estimates of watershed conditions that Reclamation uses to predict available water supplies and usage. Information such as watershed conditions, storage conditions, Klamath River flow requirements, Upper Klamath Lake elevation requirements, and estimated Project water use (irrigation and refuges) are used to develop an annual operation plan. The annual operation plan is presented to the water user community as soon as practicable, usually in April/May. The plan estimates how much water is available to meet Project demands.

NRCS forecasts often change as the year continues on, getting more accurate as time goes by. However, there is still a level of error in those forecasts; therefore, a conservative approach when using the forecasts for planning is a better practice for the Klamath basin. From January on, Reclamation conservatively uses these forecasts (as they are updated) to plan to fill storage reservoirs, provide winter water supplies to refuges and irrigators, and provide downstream flows. During these winter/spring months, Reclamation coordinates with water users, the U.S. Fish and Wildlife Service, National Marine Fisheries Service, the four Klamath basin tribes, and other stakeholders as appropriate while developing our annual operation plan.

Reclamation carries out water management activities within two primary areas of the basin. The first is the Shasta/Trinity River Diversion Project that includes Claire Engle Lake in the Trinity River subbasin. This project is operated within the context of the Central Valley Project, which is discussed further in the Sacramento and San Joaquin basin section of this report (chapter 7). The second is the Klamath Project located in the upper basin above Iron Gate Dam (figure 21). The irrigable lands of the Klamath Project are in south-central Oregon (62%) and north-central California (38%). The Klamath Project provides water to approximately 210,000 acres of cropland. Klamath Project water supplies originate from Upper Klamath Lake and the Klamath River as well as the closed basin supplies captured in Clear Lake Reservoir, Gerber Reservoir, and Lost River located in the vicinity of the Klamath Project delivery area (figure 21).

Climate varies considerably within the Klamath River basin. Precipitation is generally wetter towards the coast and on the windward side of coastal mountain ranges. Precipitation conditions tend to decrease towards the east and are relatively arid over the northern reaches of the basin. Mean-annual temperature in the lower basin is warmer than the upper basin. The lower basin also experiences less variation in seasonal temperatures.

4.2 Historical Climate

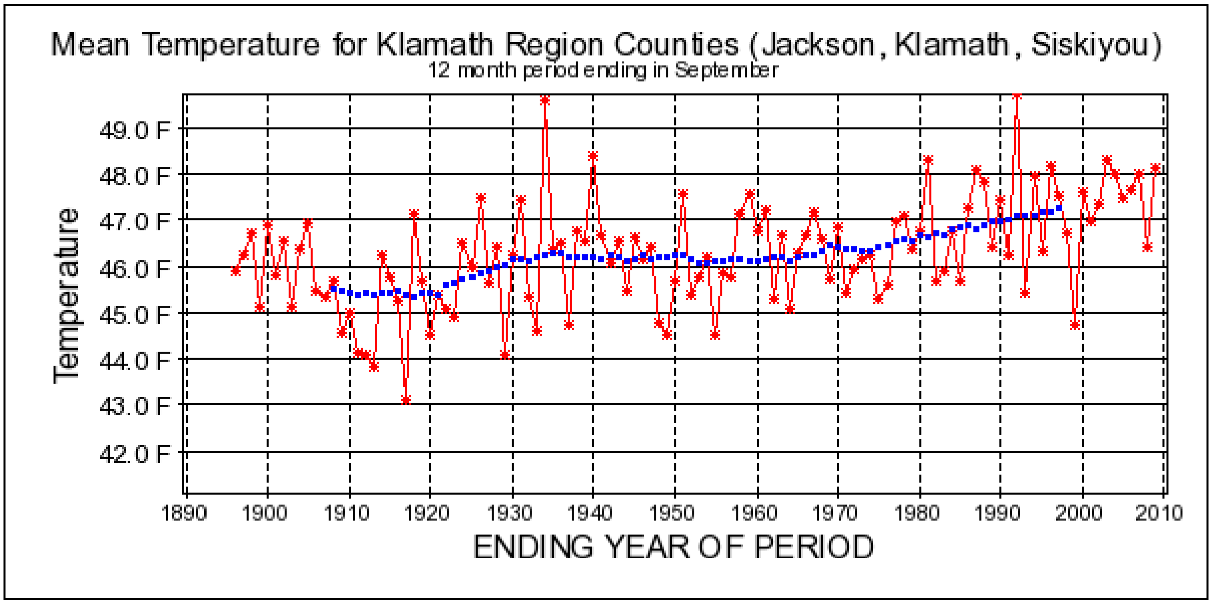
Over the course of the 20th century, warming has been prevalent over the Klamath River basin. Basin average mean-annual temperature has increased by approximately 2 °F during the course of the 20th century within the portion of the basin located over Jackson and Klamath Counties in south-central Oregon and Siskiyou County in north-central California (figure 22). However, throughout much of the period of record, large variations in annual temperature has been observed.

Warming has not occurred steadily throughout the 20th century. The basin average temperature increased steadily from the beginning of the 20th century to the 1930s; but from the 1930s to the 1970s, it generally remained unchanged (figure 22, top panel). Since the 1970s, the basin average temperature has steadily increased.

Basin annual precipitation has fluctuated considerably during the past century (figure 22, bottom panel) generally varying between 20 to 45 inches. Relative to annual temperature, any trend in mean-annual precipitation during the period of record seems less apparent. It appears that a small decrease in mean-annual precipitation may have occurred from the early 1900s to the 1920s, followed by an increase that lasted until roughly the 1940s. Since the 1940s, mean-annual precipitation is relatively steady for the remainder of the 20th century.

4.3 Historical Hydrology

Historical runoff in the Klamath River basin varies considerably from year-to-year. The basin can experience different conditions (wetter or drier) on an annual basis in the lower windward areas to upper leeward areas. This geographic variation in runoff is generally less pronounced in the Klamath River basin than in the other basins described within this report (e.g., Columbia, Colorado, Missouri). The Klamath basin tends to experience seasonal climate, whereas the other basins span a large enough region that seasonal climate can vary significantly across the basin extent. A review of historical information in the Klamath River basin shows that some runoff trends within the basin may be apparent depending on the location and historical period that is assessed. However, evaluation of these trends suggests that they are relatively weak to insignificant.



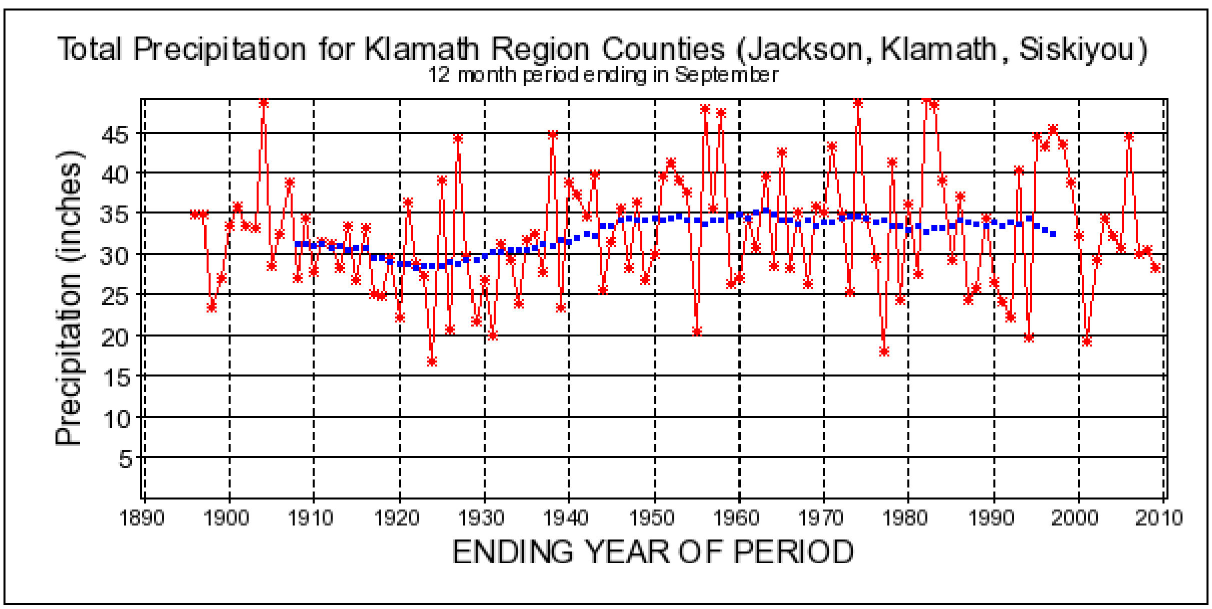


Figure 22. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Klamath River Region.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/ Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

Coincident with the climate trends discussed in the previous section, the Western United States and Klamath River basin have also experienced a general decline in spring snowpack, reduction in the amount of precipitation falling as snow in the winter, and earlier snowmelt runoff between the mid- and late-20th century (Knowles et al. 2007; Regonda et al. 2005). Annual peak discharge records indicate that, due to a number of factors, an assessment of whether observed changes are due to natural climate variability or climate change is not possible (Villarini et al. 2009).

The changes discussed in the previous paragraphs over regional drainages such as the Columbia River Basin are sensitive to the uncertainties of station measurements as well as the period of analysis and location being analyzed. For the entire Western United States, observed trends of temperature, precipitation, snowpack, and streamflow might be partially explained by anthropogenic influences on climate (e.g., Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009). However, it remains difficult to attribute observed changes in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends in precipitation (Hoerling et al. 2010) and for trends in basin-scale conditions rather than at the larger Western United States scale (Hidalgo et al. 2009).

4.4 Future Changes in Climate and Hydrology

While the previous section focused on historical conditions, this section summarizes results from studies focused on future climate and hydrologic conditions within the Klamath River basin. Section 4.4.1 focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on within this document.

4.4.1 Projections of Future Climate and Hydrology

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the perspective of basin-average and, secondly, as those climate conditions are distributed throughout the basin. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented; and, finally, climate and snowpack changes translated into effects on annual and seasonal runoff as well as acute runoff events relevant to flood control and ecosystems management are discussed.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections, and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Klamath River basin may increase steadily during the 21st century (figure 23). The Klamath River above Klamath, California, (figure 21) is projected to increase by approximately 5–6 °F during the 21st century, with range of annual possibility widening through time. Projected temperatures averaged over just the upper portion of the basin (Klamath River above Iron Gate Dam) are projected to have a similar trend. The ensemble mean of projections indicates that mean-annual precipitation, averaged over either subbasin (figure 23), is not expected to change significantly through the 21st century.

Projection of climate change is geographically complex over the Klamath River basin, particularly for precipitation.. For example, consider the four decades highlighted on figure 23 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, annual average temperatures are generally cooler in the interior plateau areas of the upper basin (figure 24, top left panel). Warmer temperatures are observed in lower lying areas of the lower basin and near the California coast. Precipitation is generally greater in the lower basin, particularly along the mountainous rim, and lesser over of the plateau areas of the upper basin (figure 25, top left panel). Looking at climate change, temperature changes are generally uniform over the basin but with perhaps less warming near the coast. They also steadily increase through time (figure 24). For precipitation, similar geographic uniformity is found (figure 25). Precipitation, unlike temperature, may experience a change from increasing to decreasing for the same location through the decades. The overall precipitation change projection suggests a slight increase over the entire basin during the early 21st century, transitioning to a northern increase and southern decrease by the 2070s.

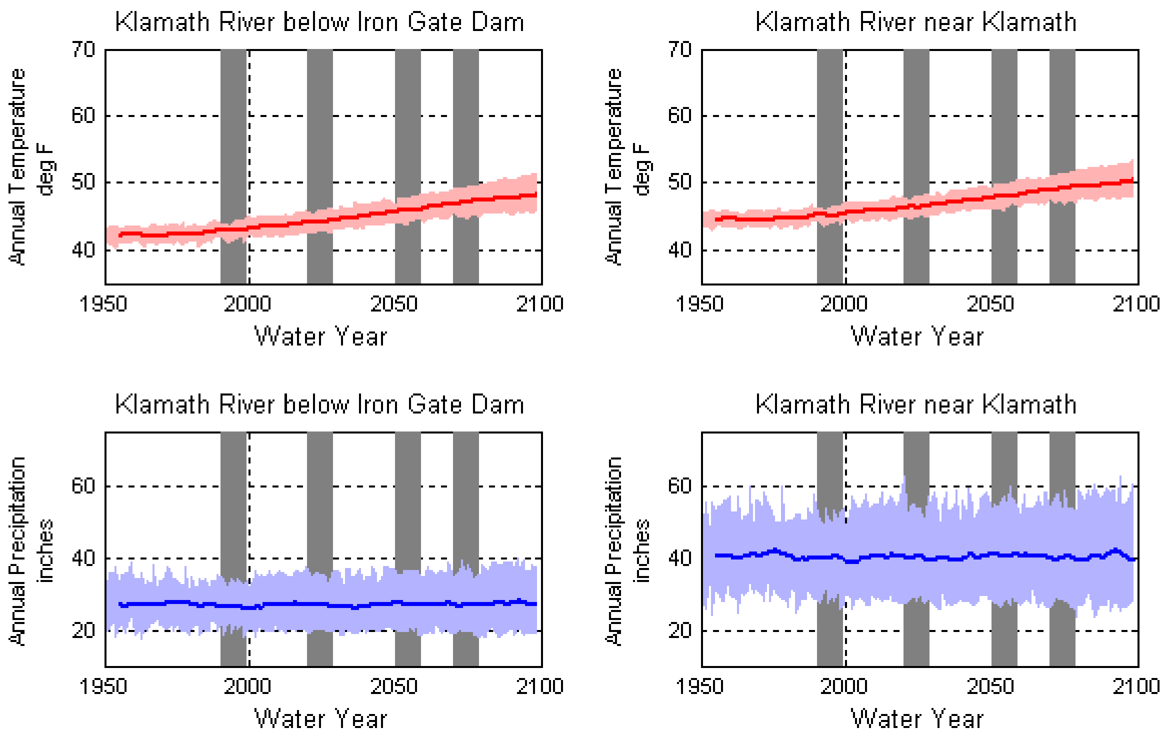


Figure 23. Simulated annual climate averaged over Klamath River subbasins.

Figure 23 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

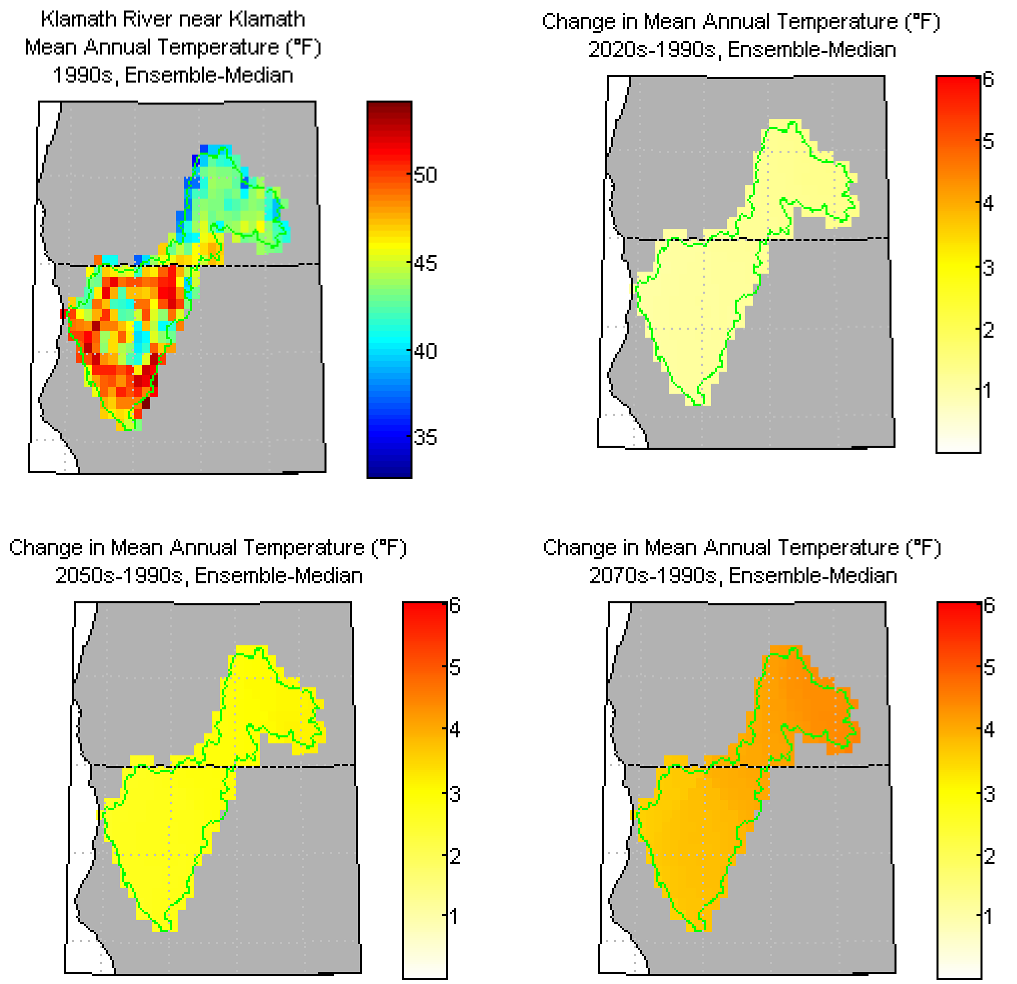


Figure 24. Simulated decade-mean temperature over the Klamath River basin above Klamath, California.

Figure 24 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

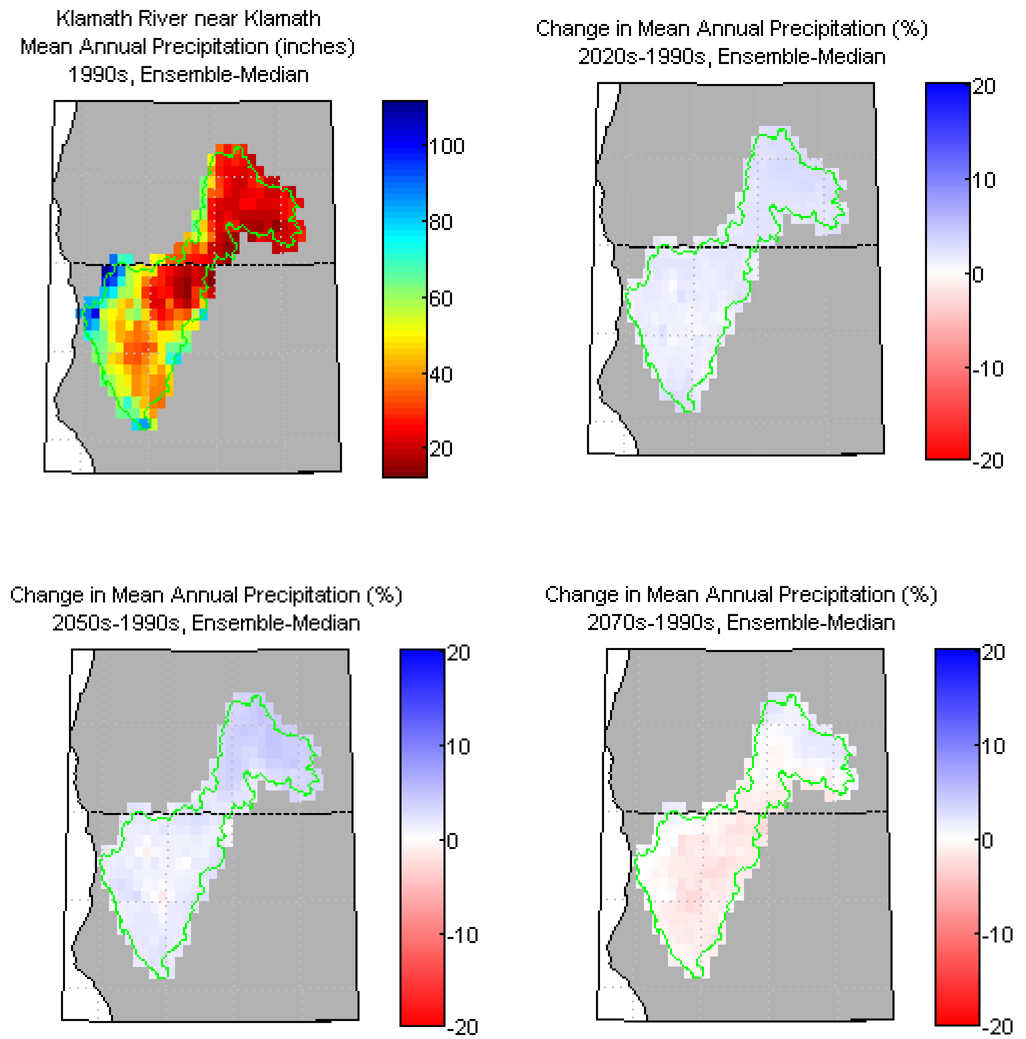


Figure 25. Simulated decade-mean precipitation over the Klamath River basin above Klamath, California.

Figure 25 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

Temperature and precipitation changes are expected to affect hydrology in various ways including snowpack development. As noted previously, increased warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify changes in snowpack, it is apparent that the projected warming in the Klamath River basin tends to dominate projected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 26). Snowpack decrease is projected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. This is particularly the case for the lower elevation valley areas throughout the basin, as well as the interior plateau areas of the upper basin.

Changes in snowpack within the Klamath River basin will change the availability of natural water supplies. These changes may be to annual runoff, and changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would offset or amplify the effect. Results from Reclamation (2011a) suggest that annual runoff changes are generally consistent but do vary slightly by location in the Klamath River basin (figure 27), depending on baseline climate and the projected temperature and precipitation changes. For example, in the early 21st century, slight increases in annual runoff are projected in the northeastern upper reaches of the basin (e.g., Williamson River below Sprague River) compared to smaller increases at runoff locations further downstream that include southern reaches of the basin (e.g., Klamath River near Klamath, California). As temperature continually increases throughout the 21st century and precipitation may be reduced by the 2070s (figure 24), the Klamath River near Klamath, California, may change to a slight decrease in annual runoff (figure 26).

The seasonality of runoff is also projected to change. Warming may lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This conceptually leads to increases in December-March runoff and decreases in April-July runoff. However, the degree to which these conceptual results bear out in the Klamath River basin appears to vary by subbasin (figure 27). The concept is supported by results that show increased mean seasonal volume by the 2020s and a trend toward greater increases by the 2070s in all of the subbasins for the December through March seasonal runoff. Additionally, the concept is supported for April through July seasonal runoff where projected warming may lead to not only spring snowpack decline (figure 26) but also reduction in spring-summer

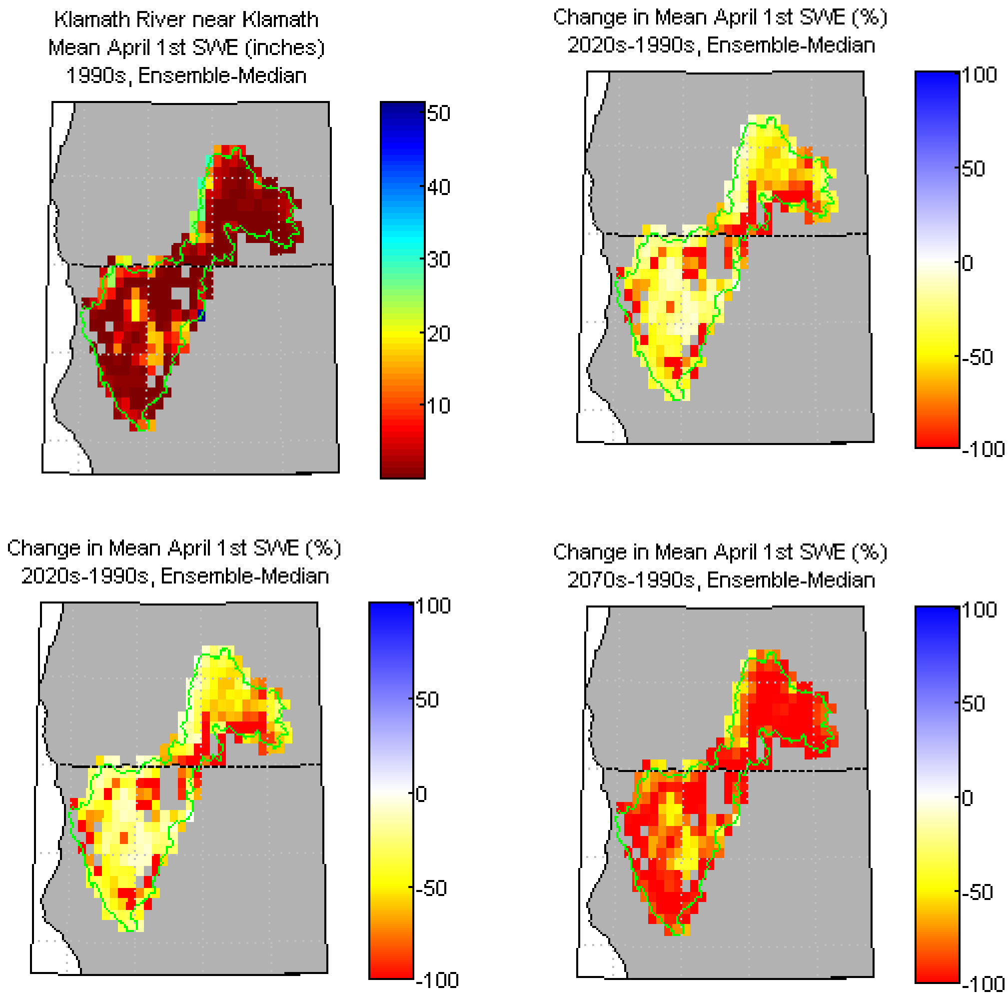


Figure 26. Simulated decade-mean April 1st Snowpack over the Klamath River basin above Klamath, California.

Figure 26 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

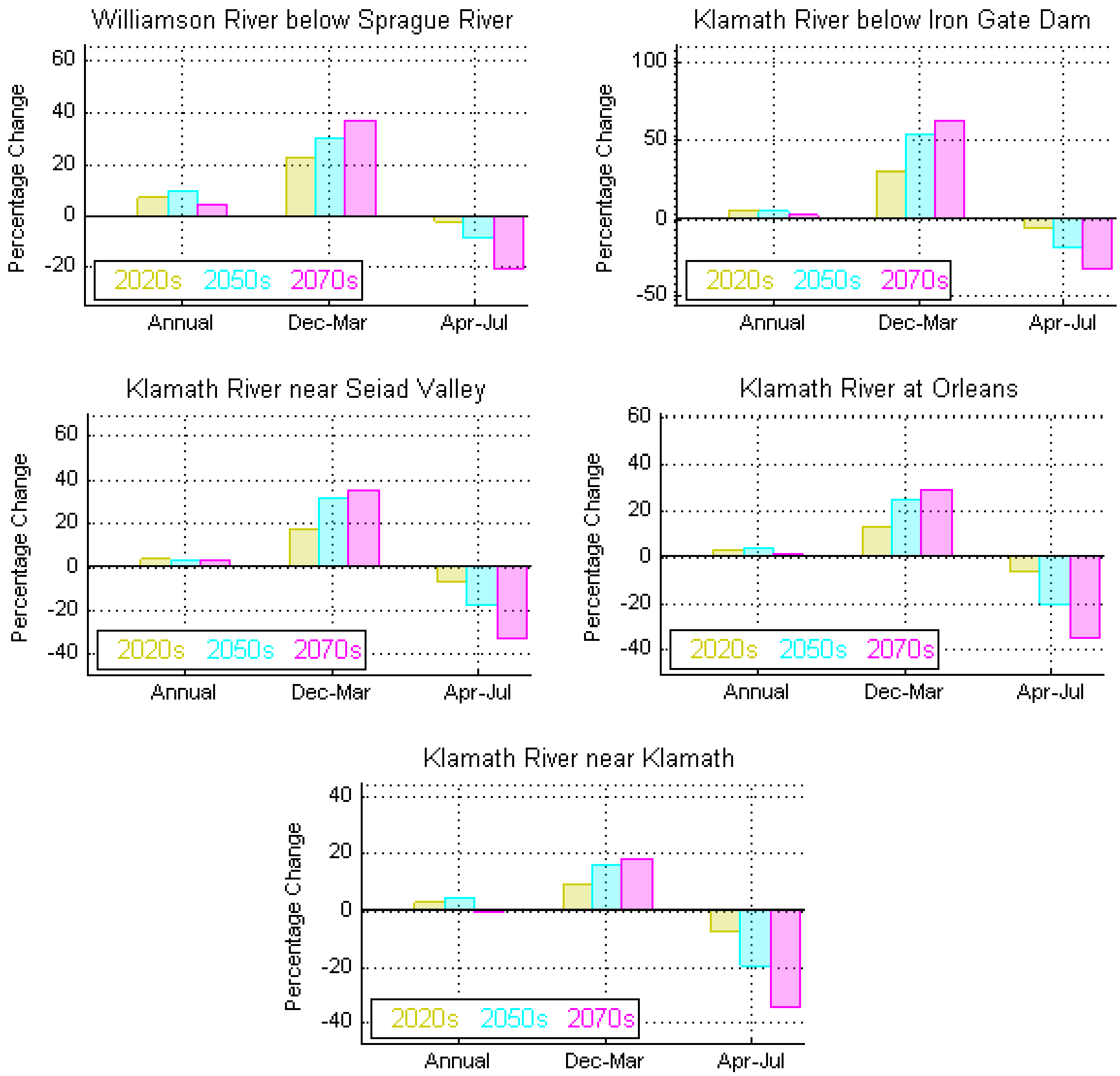


Figure 27. Simulated changes in decade-mean runoff for several subbasins in the Klamath River basin above Klamath, California.

Figure 27 presents Annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

runoff. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to acute runoff events relevant to Klamath River ecosystem management is also of interest, although there is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. Utilizing annual maximum- and minimum-week runoff as metrics of acute runoff events of, respectively (figure 28), it appears that projected trends in annual maximum-week runoff may vary by subbasin. For example, the northeastern upper reaches (e.g., Williamson River below Sprague River) show results where annual maximum-week runoff remains relatively stable through the 21st century. In contrast, runoff locations located further downstream and including a greater portion of the lower basin (e.g., Klamath River near Klamath, California) show gradually increasing annual maximum-week runoff. For annual minimum-week runoff, results are generally consistent across the subbasins, where gradual declines are projected during the 21st century, more so for locations including the southern reaches of the basin. However, in spite of these findings, it is noted that to understand potential changes in acute runoff events such as these and implications of such changes for reservoir management in the Klamath River basin, more indepth analyses are warranted.

A summary of climate and hydrologic changes is provided in table 3 for three subbasins of the Klamath River basin: Williamson River below Sprague River, Klamath River near Seiad Valley, and Klamath River near Klamath, California. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

4.4.2 Other Studies of Future Climate and Hydrology

Relative to other basins featured in this report, the Klamath River basin has been the subject of relatively few studies on future climate and hydrologic changes. However, a nationwide future climate and hydrologic assessment was recently completed by the U.S. Geological Survey (Markstrom et al. 2011), which included the Sprague River among the study basins. The study had similar findings to Reclamation (2011a) both for December–March runoff increases in

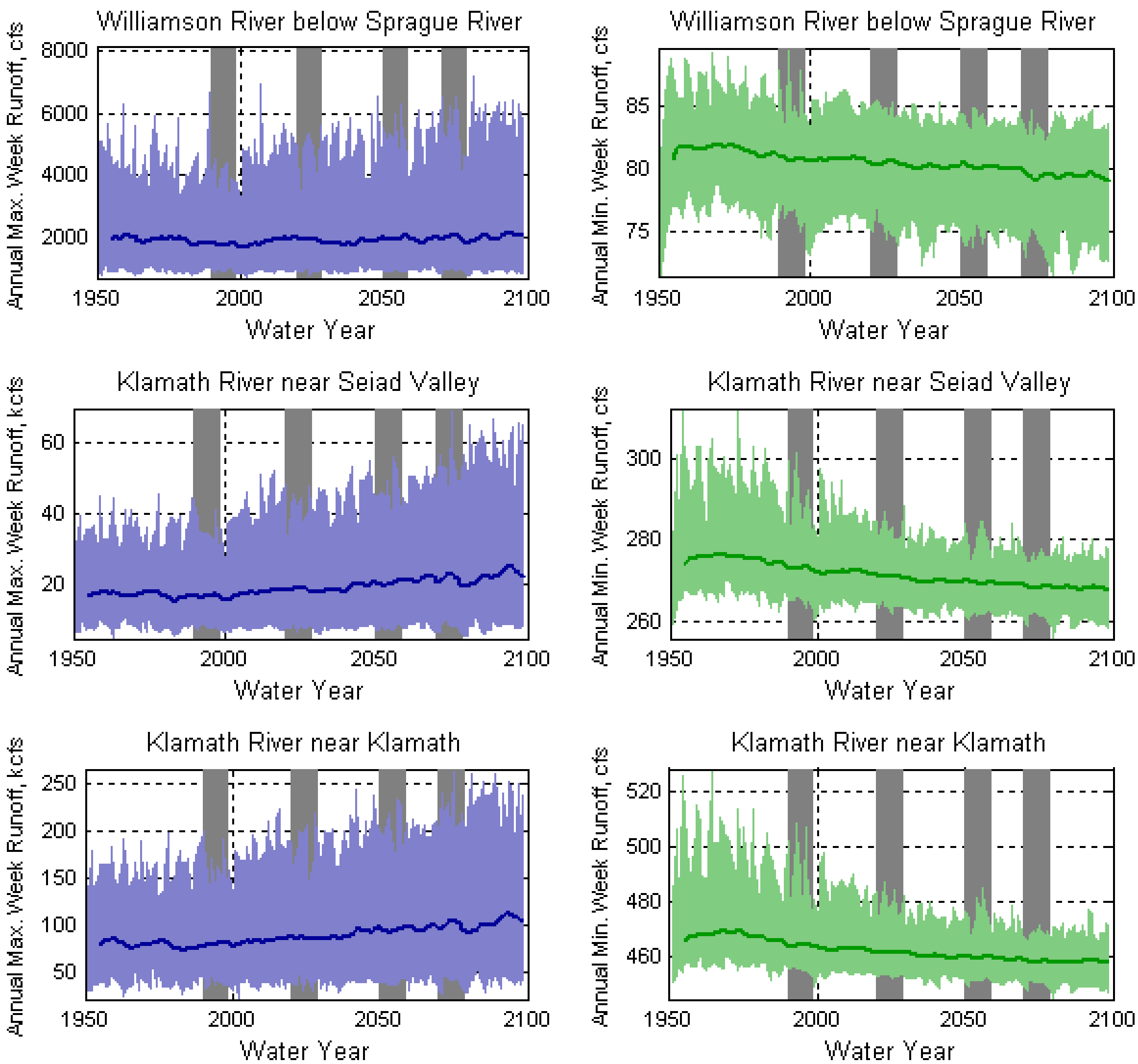


Figure 28. Simulated annual maximum and minimum week runoff for several subbasins in the Klamath River basin**.**

Figure 28 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

Table 3. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Klamath River basin

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Williamson River below Sprague River			
Mean Annual Temperature (°F)	1.3	3.0	4.3
Mean Annual Precipitation (%)	2.4	2.7	2.2
Mean April 1st Snow Water Equivalent (%)	-64.3	-83.1	-94.7
Mean Annual Runoff (%)	7.1	9.6	4.4
Mean December–March Runoff (%)	22.3	29.7	36.7
Mean April–July Runoff (%)	-2.0	-8.3	-20.5
Mean Annual Maximum Week Runoff (%)	8.8	10.6	10.9
Mean Annual Minimum Week Runoff (%)	-0.4	-0.8	-1.6
Klamath River near Seiad Valley			
Mean Annual Temperature (°F)	1.2	2.8	4.1
Mean Annual Precipitation (%)	1.3	2.6	1.1
Mean April 1st Snow Water Equivalent (%)	-47.6	-68.6	-83.3
Mean Annual Runoff (%)	3.7	2.9	3.5
Mean December–March Runoff (%)	16.9	31.2	35.1
Mean April-July Runoff (%)	-6.5	-17.6	-32.6
Mean Annual Maximum Week Runoff (%)	11.8	24.0	30.1
Mean Annual Minimum Week Runoff (%)	-0.7	-1.2	-1.6
Klamath River near Klamath			
Mean Annual Temperature (°F)	1.2	2.7	4.0
Mean Annual Precipitation (%)	0.1	2.2	-0.2
Mean April 1st Snow Water Equivalent (%)	-46.9	-70.9	-85.3
Mean Annual Runoff (%)	2.6	4.0	-1.0
Mean December–March Runoff (%)	8.7	15.5	17.8
Mean April–July Runoff (%)	-7.5	-19.5	-34.2
Mean Annual Maximum Week Runoff (%)	7.9	18.5	24.9
Mean Annual Minimum Week Runoff (%)	-0.5	-0.9	-1.3

streamflow and decreases in April–June by the end of the 21st century. Their results also suggest that, by the end of the 21st century, the timing of peak streamflow from the Sprague River is projected to shift from April to March.

4.5 Future Implications for Water and Environmental Resources

4.5.1 Water Supply, Reservoir Operations and Flood Management

Based on current reservoir operational constraints (e.g., storage capacity, constraints on reservoir water releases to satisfy various obligations), projected effects on runoff seasonality from warming without precipitation change are likely to lead to reduced water supplies. This expectation is based on current operating conditions that limit storage opportunities during the winter runoff, which are controlled by flood control considerations at basin reservoirs, and that increased winter runoff under climate change will not necessarily translate into increased storage of water leading into the spring season. Capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during the spring and early summer season likely would translate into reductions in storage capture and likewise reductions in water supply for warm season delivery. When the future climate scenario is adjusted to reflect projected warming with precipitation increase (e.g., over the upper reaches tributary to Upper Klamath Lake), the conceptual effects on reservoir operations are less obvious, since changes in precipitation can offset some of the warming effects on spring–summer runoff, as illustrated in the previous section.

4.5.2 Hydropower

Electricity demand from hydropower generation and other sources generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

4.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

4.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

4.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

4.5.6 Water Demands

Potential climate changes to agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures; increased atmospheric carbon dioxide levels; and changes in precipitation, winds, humidity, atmospheric aerosol, and ozone levels.

Furthermore, these natural system changes must be considered in combination with socioeconomic changes including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Agricultural irrigation is the predominant water demand on Reclamation reservoir systems within the upper Klamath River basin. Given that the atmosphere's moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, crop water demands respond to atmospheric carbon dioxide ozone and potential evapotranspiration, in addition to temperature and precipitation (e.g., Baldocchi and Wong 2006; Bloom 2010). Additionally, agricultural water demand could decrease due to crop failures caused by changes in pests and diseases in the future. Seasonal volume of agricultural water demand could increase if growing seasons become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century. It is projected that, by the end of the 21st century, the growing season may be more than 2 weeks longer than the typical growing season of the late 20th century (Gutowski et al. 2008). Another study suggests that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Climate change also could result in changed demand for instream flow or reservoir release to satisfy other system objectives, including ecosystem support, hydropower generation, municipal and industrial water deliveries, river and reservoir navigation, and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures resulting in hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by thermoelectric power production and industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production also could be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on water allocations from year-to-year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic, land use changes, and other nonclimate factors.

Other consumptive uses associated with agricultural reservoir systems management include reservoir evaporation and losses during water conveyance and onfarm application. These types of system losses can be significant (e.g., evaporation from Upper Klamath Lake). Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

5. Basin Report: Missouri

5.1 Basin Setting

The headwater tributaries of the Missouri River rise along the Continental Divide in southwestern Montana. These tributaries convey snowmelt runoff to the Gallatin, Madison, and Jefferson Rivers that converge near Three Forks, Montana, to create the Missouri River. The Missouri River then flows approximately 2,500 miles through Montana, North Dakota, South Dakota, Nebraska, Iowa, Kansas, and Missouri to its confluence with the Mississippi River near St. Louis, Missouri.

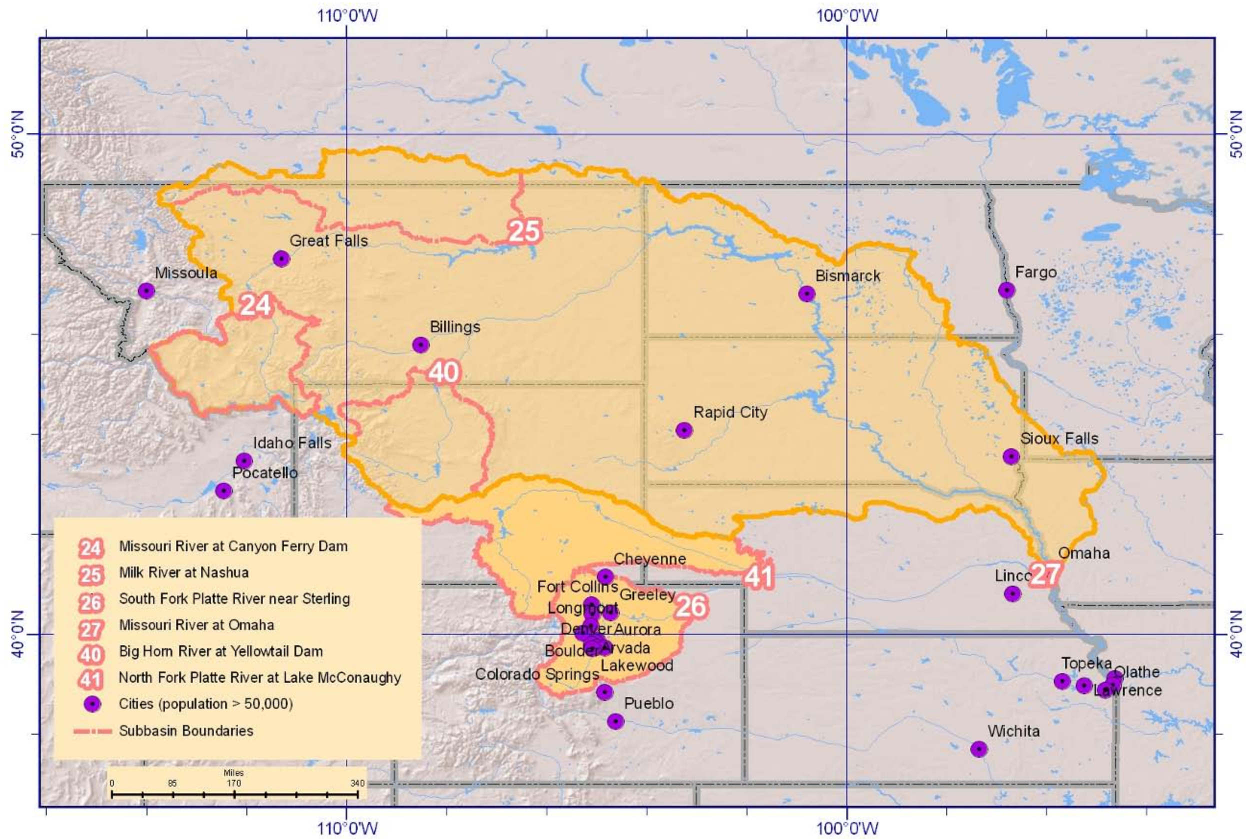


Figure 29. Missouri River basin and runoff-reporting Locations for this report.

The Missouri River basin is the longest river in the United States and has a watershed of over 500,000 square miles. It includes portions of 10 States and one Canadian province and encompasses about one-sixth of the conterminous United States. Although the river drains the largest watershed within the United States, it produces annual yields (40,000,000 acre-feet) significantly less than either the Columbia (199,000,000 acre-feet) or Ohio (181,000,000 acre-feet) Rivers. Low annual yield, in combination with a large watershed and socioeconomic factors, contribute to conflict in management and use of the river throughout the basin.

Basin topography varies from glaciated mountain ranges to flat and rolling grasslands to wide flood plain valleys. Climate and vegetation are similarly varied ranging from alpine tundra environments to subhumid grasslands and temperate forests. The majority of the basin consists of rolling plains with agriculture the predominant use of the land.

The Missouri River crosses the 98th meridian in northeastern South Dakota. This meridian roughly divides the United States between relatively arid and humid (e.g., 20 inches or more of annual precipitation) climates. The Missouri River basin exhibits strong temperature and precipitation gradients consistent with larger continental gradients in North America. Mean annual temperatures decrease northward, and average annual precipitation increases from west to east. In the western basin, most precipitation falls as snow. Most of the precipitation in the eastern basin falls as rain.

Reclamation coordinates with many entities within the Missouri River basin. Each spring, Reclamation Area Offices in Montana, Wyoming, and Colorado meet with States, water users, instream and flat-water interests, and others to present tentative reservoir operating plans for comment and discussion. Since the facilities are in headwater basins that are primarily influenced by snow melt runoff, operating plans exhibit a good degree of forecasting accuracy; and, hence, reasonable adjustments oftentimes can be made. Similar meetings are held for facilities in the Plains States (Dakotas, Nebraska and Kansas). Reclamation listens to comments, concerns, and suggestions but is the sole decisionmaker in accordance with the Federal Advisory Committee Act. Additional coordination activities include longer range planning efforts. Established in the fall of 2008, the Missouri River Recovery Implementation Committee (MRRIC) serves as a basin-wide collaborative forum to develop a shared vision and comprehensive plan for Missouri River recovery. Authorized by Congress in Section 5018 of the 2007 WRDA, the MRRIC is tasked with making recommendations and providing guidance on a study of the Missouri River and its tributaries known as the Missouri River Ecosystem Recovery Plan (MRERP). Reclamation is a member of MRRIC and is working with the USACE to develop climate scenarios for MRERP and Missouri River Authorized Purposes.

Since the USACE began debris snagging and other river maintenance activities in 1838, issues along the Missouri River related to competing uses of water have been commonplace. The USACE and Reclamation developed separate water management plans focused on flood control, navigation, and water scarcity and the need for irrigation, respectively. Congress passed the Flood Control Act of 1944 that included both the USACE and Reclamation management plans for the river that came to be known as the Pick-Sloan Missouri Basin Program (Pick-Sloan Program). The Flood Control Act of 1944 also included the O'Mahoney-Millikin Amendment, making navigation subordinate to beneficial consumptive uses of water west of the 98th meridian. Section 9 of the Flood Control Act of 1944, as amended, authorized the Pick-Sloan Program for flood control, navigation, irrigation, power, water supply, recreation, fish and wildlife, and water quality.

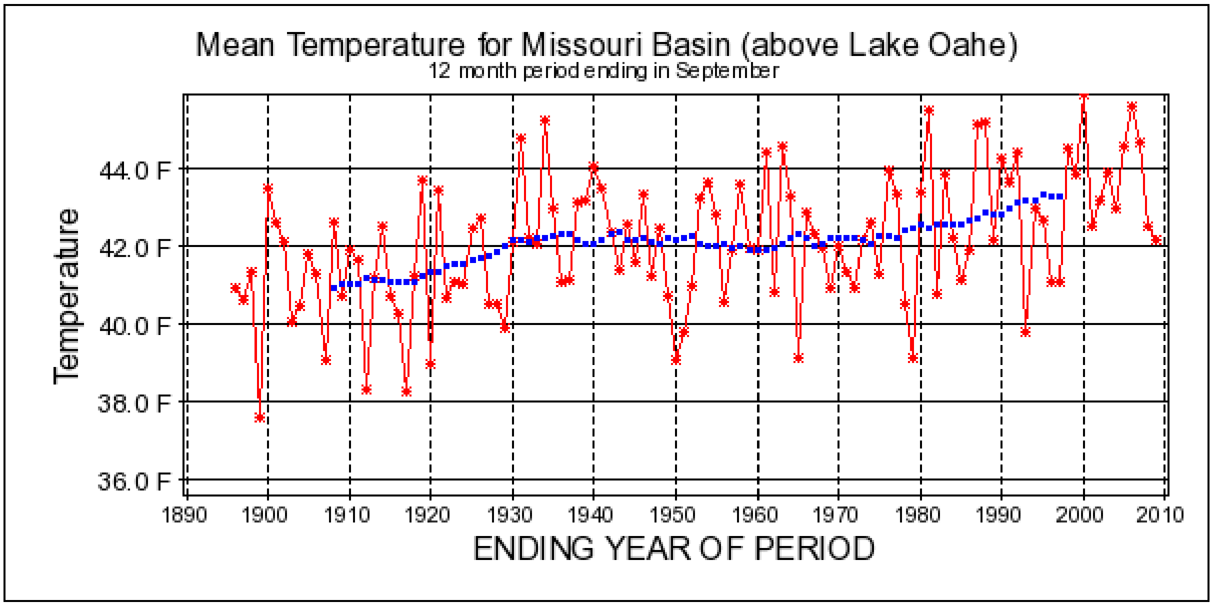
As a result of the Pick-Sloan Program, the USACE constructed six mainstem dams on the Missouri River, and Reclamation constructed over 40 dams on basin tributaries. Reclamation's development in the basin focused on agricultural irrigation in the upper basin States west of the 98th meridian.

5.2 Historical Climate

Over the course of the 20th century, warming has been prevalent over the Missouri River basin. Focusing on the portion of the basin above Lake Oahe (figure 30), it appears that the basin average temperature has increased by approximately 2 °F during the course of the 20th century. However, throughout much of the period of record, large variations in annual temperature has been observed.

Warming has not occurred steadily throughout the 20th century. The basin average temperature has increased steadily from the beginning of the 20th century to the 1930s; but then from the 1930s to roughly 1980, it generally remained unchanged (figure 29, top panel).

The warming depicted in figure 30 is consistent with other studies of historical climate within the region. For example, Easterling et al. (1997) and Karl et al. (1996) collectively reported that the Great Plains has warmed 1.8–3.6 °F over the last 100 years. Those studies also suggested that the northern portion of the Great Plains, including the Missouri River basin, has experienced relatively greater warming compared to neighboring regions with slightly greater warming during winter. Significant upward trends in average annual minimum and maximum temperatures have been documented for Montana and western North Dakota (Norton 2010). The prairie pothole region along the northern and eastern margins of the basin generally has become warmer during the 20th century (Millett et al. 2009). Mean annual temperatures also have been found to



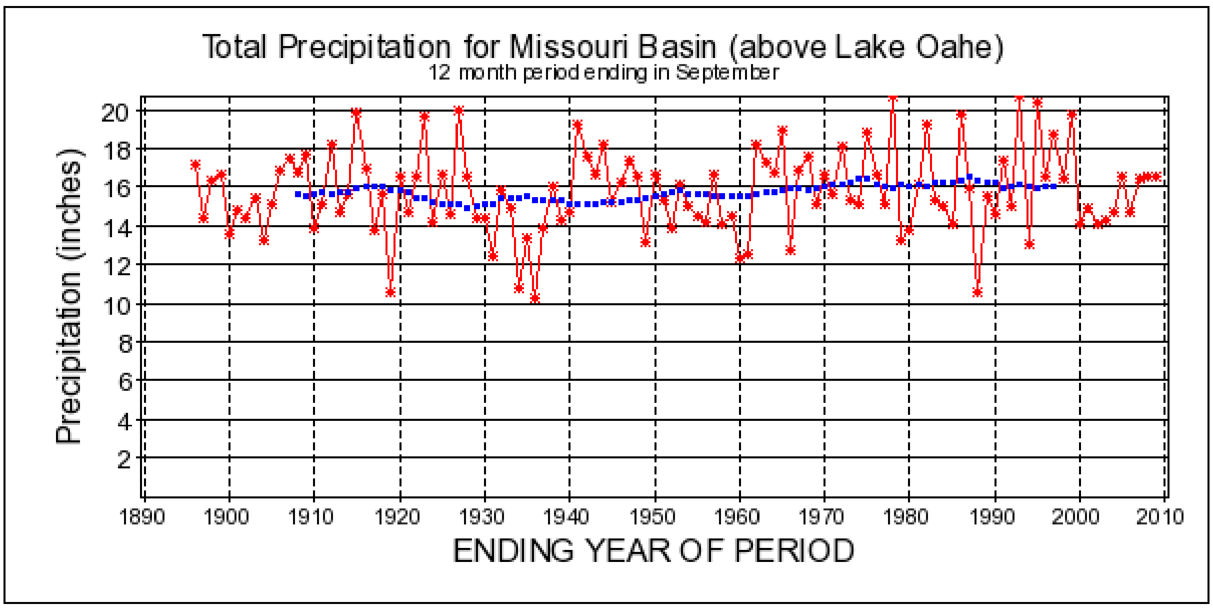


Figure 30. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Missouri basin above Lake Oahe.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

increase in the southern margins of the basin (e.g., northeastern Colorado [Alward 1999] as well as southern Nebraska and northern Kansas [Norton 2010]).

Basin annual precipitation has fluctuated considerably during the past century (figure 30, bottom panel), generally varying from 10–20 inches per year. Relative to annual temperature, any trend in mean-annual precipitation during the period of record is less apparent. Other studies also have reported historical precipitation increases over the upper reaches of the basin (e.g., wetter conditions over much of the prairie pothole region [Millett et al. 2009], except for eastern Montana and North Dakota). In the southwestern reaches of the basin, annual precipitation has also been reported as increasing since the 1970s (e.g., northeastern Colorado [Alward 1999]).

5.3 Historical Hydrology

Historical runoff in the Missouri River basin varies considerably from year to year. Annual runoff departures from normal conditions also can vary geographically within the basin, where during any particular year, some areas of the basin may experience relatively greater runoff conditions while others experience relatively lesser conditions. On a monthly to seasonal basis, there are two prominent peaks in the Missouri River annual cycle. The first is a minor peak during early spring supplied by lowland snowmelt, and the second is a major peak during early summer supplied by mountain snowmelt.

Analysis of historical hydrology indicates that some changes may be apparent depending on the location and period of record being studied but are considered relatively weak.[7] These results are generally consistent with other studies that have explored historical hydrologic trends in different parts of the basin and for various historical periods. One study assessed changing streamflow conditions throughout the basin that apparently occurred during roughly the last half of the 20th century (Anderson et al. 2008a). Their findings suggested that trends varied from weak to significant and that significant trends in the eastern portion were generally increasing while those in the western portion were generally decreasing. Another study reported declining precipitation and streamflow trends in the increase in the

[7] Trend significance was assessed using statistical testing during the period of 1951–1999 applied to historical simulated runoff results under observed historical weather conditions (Reclamation 2011a). Trends were computed and assessed for four Missouri basin locations, focusing on annual and April–July runoff. In all cases, computed trends were judged to not be statistically significant with 95-percent confidence.

southern margins of the basin (e.g., northeastern Colorado southern reaches of the basin (e.g., southern Nebraska and northern Kansas [Norton, 2010]).

Historical trend analyses are sensitive to the location where data are collected and evaluated as well as the period of analysis. For example, Norton (2010) found significant downward trends in annual precipitation and streamflow in eastern Montana and western North Dakota, which differ from the apparent precipitation trend depicted within figure 30. This inconsistency likely results from the relative size of the basins being analyzed, with results on figure 30 representing a larger region condition compared to that over eastern Montana and western North Dakota.

There is evidence suggesting that the Missouri River basin may have experienced relatively wetter conditions during the 20th century compared to prior centuries as well as relatively less annual runoff variability. These findings are based on evaluation of tree ring records and reconstruction of upper basin annual runoff prior to the period of observed record (Stonefelt 2000; Woodhouse 2001; Watson et al. 2009). For example, the worst drought observed in the 20th century likely was equaled or exceeded at least 30 times in the preceding six centuries (Gray et al. 2007). Also, within the upper Yellowstone River, it appears that the average annual runoff during the 1990s was the highest in the past 300 years (Graumlich et al. 2003). Even omitting major flood events in 1996 and 1997, the 1990s were still the sixth wettest decade of the past 300 years. Changing the focus from surplus years to drought years, it appears that over 72% of extreme dry years in Yellowstone National Park and the Yellowstone River were matched by summer drought in the upper Missouri River basin (Gray et al. 2007). Based on their tree ring reconstruction, the 1930s were the driest extended period of below-average streamflow during the last 300 years, and these flows were virtually unprecedented during the reconstruction record. For the 15 driest years in the Yellowstone River reconstruction, 12 extreme drought years were found in the reconstruction of precipitation in the neighboring Bighorn basin (Gray et al. 2004). In locations throughout North Dakota, Ashworth (1999) correlated climate with tree rings. His tree ring records display considerable variability but suggest a cyclic nature to drought in North Dakota with intense droughts recurring every 40–60 years. The 1930s drought is the most significant drought in the period of record; however, droughts occurring during A.D. 200–370, A.D. 700–850, and A.D. 1000–1200 were of greater magnitude.

5.4 Future Changes in Climate and Hydrology

This section summarizes results from studies focused on future climate and hydrologic conditions within the Missouri River basin. Section 5.4.1 focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document.

5.4.1 Projections of Future Climate

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the perspective of basin-average and secondly as those climate conditions are distributed throughout the basin. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented; and, finally, climate and snowpack changes translated into effects on annual and seasonal runoff, as well as acute runoff events relevant to flood control and ecosystems management are discussed.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Missouri River basin may increase steadily during the 21st century (figure 31). The basin-average mean-annual temperature is projected to increase by roughly 5 °F during the 21st century for the western upper reaches of the basin (e.g., Missouri River at Canyon Ferry). The projected increase is roughly 6 °F for the larger region encompassing most of the basin (i.e., Missouri River at Omaha). For both subbasin views, the range of annual possibility appears to widen through time.

Projections of mean-annual precipitation, averaged over either subbasin (figure 31), indicate to gradual increases during the 21st century. This is evident by following the ensemble median of the annual precipitation through time for both basins, noting that the condition remains relatively static during the 20th century and then begins to gradually increase during the early- to mid-21st century and continuing to increase through the end of the century. Climate projections are not in complete agreement of trend or magnitude

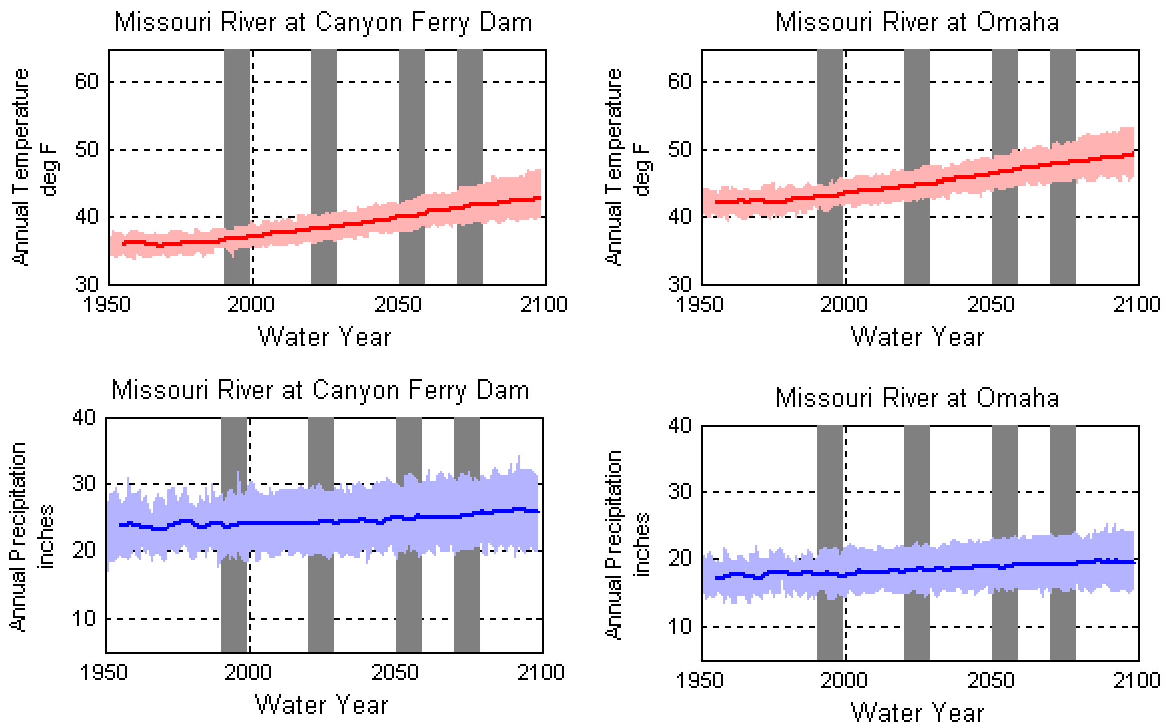


Figure 31. Simulated annual climate averaged over Missouri River subbasins.

Figure 31 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

of change. Many projections evaluated (Reclamation 2011a) indicate trends toward decreasing precipitation over the basin. Projections of climate changes are geographically complex for the Missouri River basin when climate, particularly for precipitation changes. For example, consider the four decades highlighted on figure 31 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered to be the baseline climate from which climate changes are assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, annual average temperatures are generally cooler in the high-elevation upper reaches located in the western portion of the upper basin (figure 32, top left panel). Warmer temperatures are observed over lower lying plains to the east and south. Likewise, precipitation is generally greater in the western upper reaches

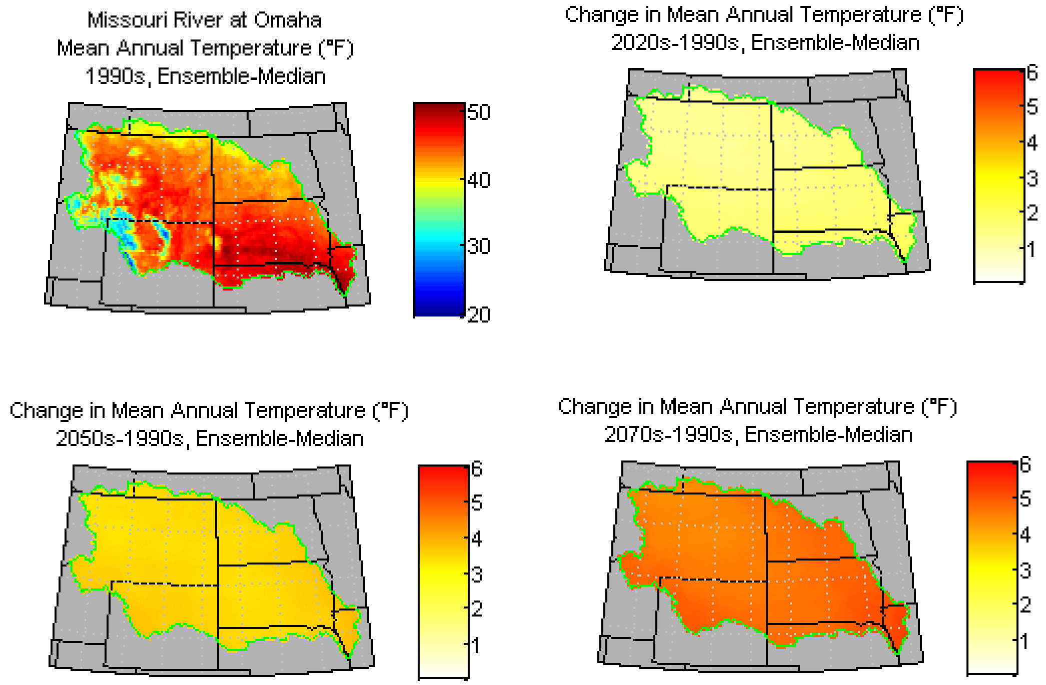


Figure 32. Simulated decade-mean temperature over the Missouri River above Omaha, Nebraska.

Figure 32 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

along the mountainous rim and over the southeastern reaches, and lesser in the high plains region located in between these two areas (figure 33, top left panel). Addressing climate change, temperature changes are generally uniform over the basin and steadily increase through time (figure 32). For precipitation, similar geographic consistency is found, although there does appear to be a general southwest to northeast gradient of change across the basin, where the southwest experiences slight decrease to slight increase from the 2020s to 2070s and the northeast experiences slight increase to greater increase from the 2020s to 2070s.

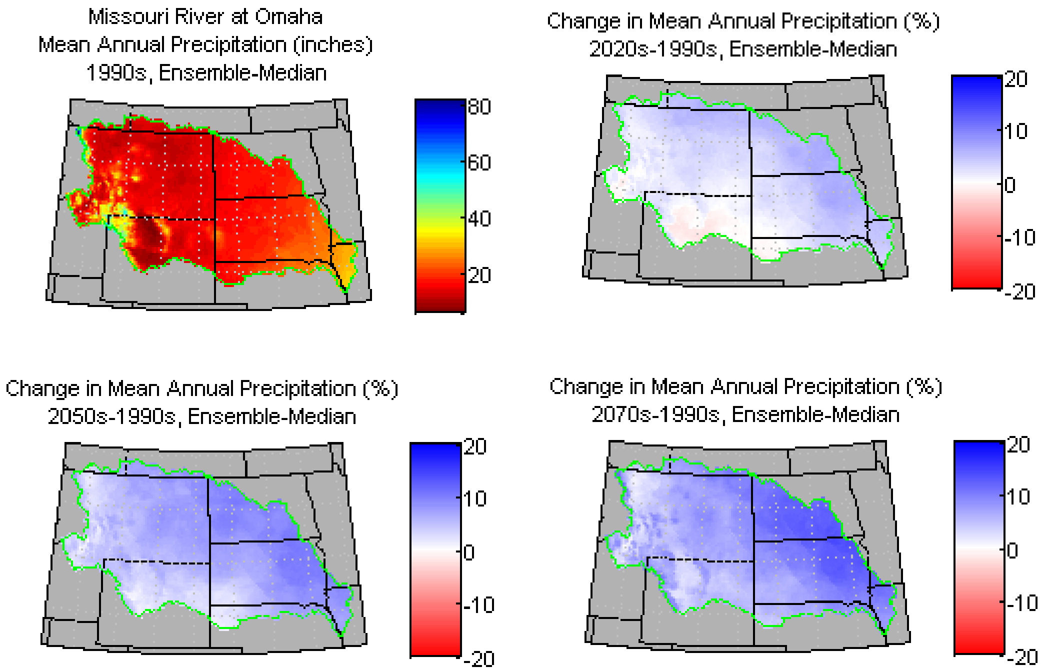


Figure 33. Simulated decade-mean precipitation over the Missouri River above Omaha, Nebraska.

Figure 33 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

Temperature and precipitation changes are expected to affect hydrology in various ways including snowpack development. As noted previously, warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify changes in snowpack, it is apparent that projected warming in the Missouri River basin dominates projected changes in snowpack (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 34). Decreases in snowpack are projected to be more substantial over the portions of the basin where baseline cool season temperatures generally are closer to freezing thresholds and more sensitive to projected warming. This is particularly the case for the eastern plains.

Changes in snowpack within the Missouri River basin will change the availability of natural water supplies. These changes may be to annual runoff and changes in runoff seasonality. For example, warming without any change to precipitation would lead to increased evapotranspiration from the watershed and decreased

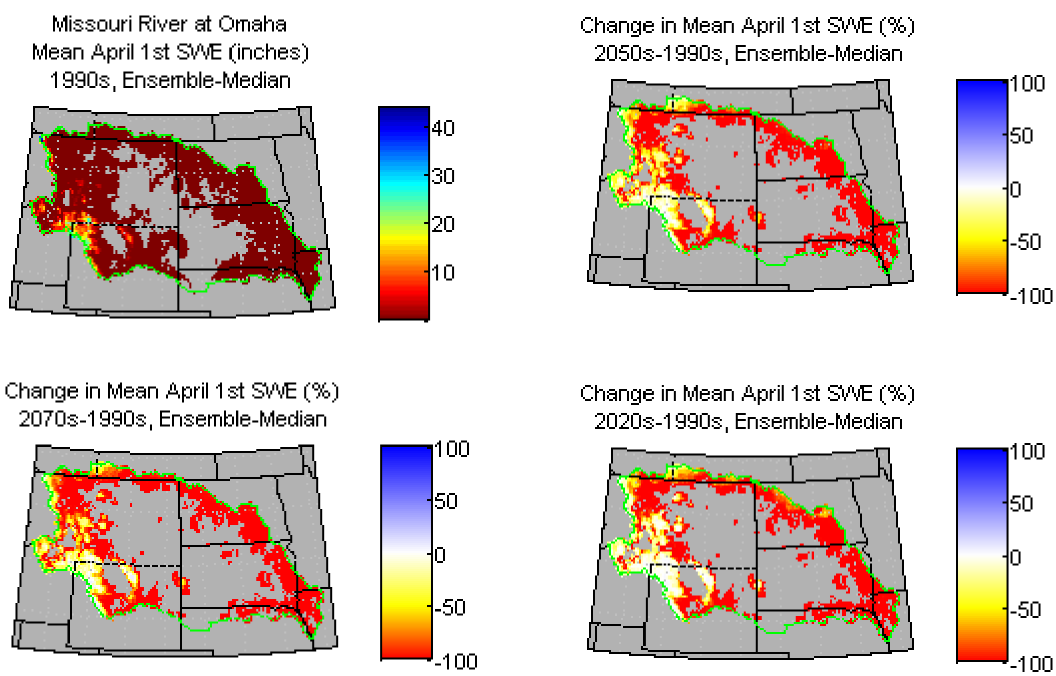


Figure 34. Simulated decade-mean April 1st snowpack over the Missouri River above Omaha, Nebraska.

Figure 34 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and the next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units are °F for baseline and change. Precipitation and snow water equivalent units are inches for baseline and percentage for change. For snow water equivalent, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would offset or amplify the effect. Results from Reclamation (2011a) suggest that annual runoff effects are generally consistent but do slightly vary by location in the Missouri River basin (figure 35), depending on baseline climate and the projected temperature and precipitation changes. For example, with the exception of the South Platte River basin, decadal-mean annual runoff is projected to increase basin-wide relative to the baseline. Decadal-mean annual runoff is projected to decrease significantly for the South Platte River basin for all months due primarily to increased temperatures and little projected change in precipitation (figure 33).

The seasonality of runoff also is projected to change. Warming is expected to lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This conceptually leads to increases in December–March runoff and decreases in April–July runoff. However, results over the Missouri River

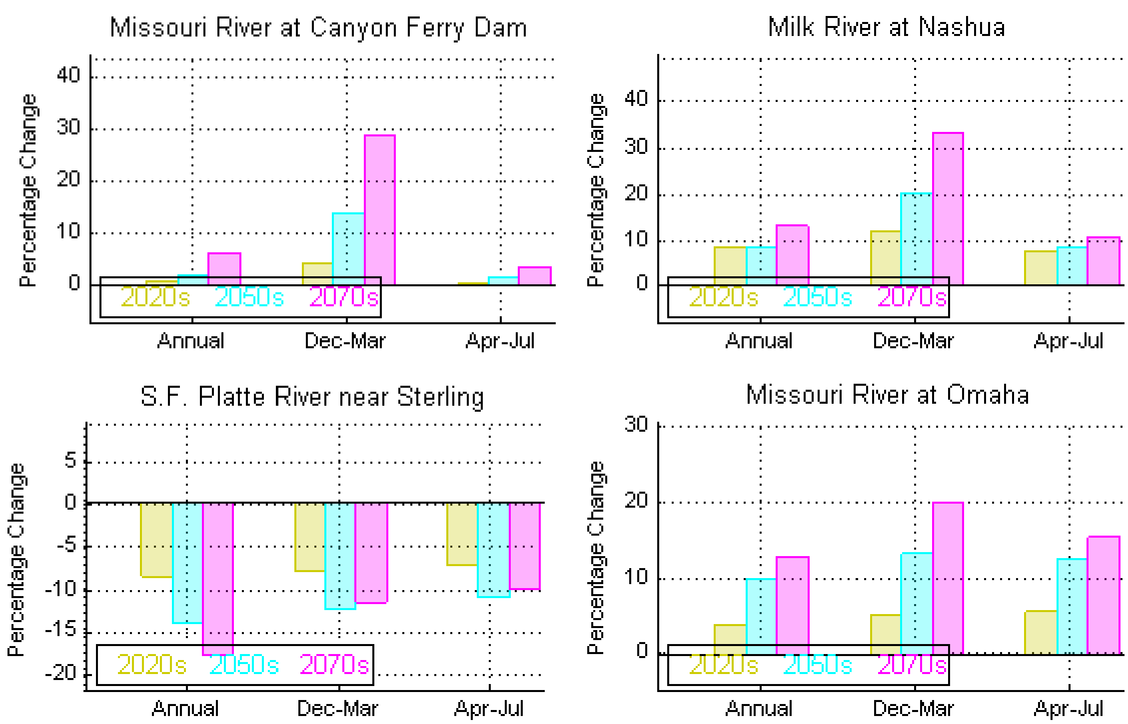


Figure 35. Simulated changes in decade-mean runoff for several subbasins in the Missouri River basin.

Figure 35 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

basin suggest that the degree to which this concept bears out depends on whether the subbasin of interest is in the mountainous western reaches over the northern and eastern high plains (figure 35). The concept is supported for December–March seasonal runoff for the Missouri River, above Canyon Ferry, which shows significant increases in mean seasonal volume during the course of the 21st century. For the other subbasins, December–March increases are more consistent with changes in mean-annual runoff, suggesting that the warming impact on cool season snowfall versus rainfall is not as significant in affecting resultant cool season runoff. The concept also does not hold well for April–July seasonal runoff, as changes in April–July runoff are generally projected to be consistent with annual runoff. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to acute runoff events relevant to Missouri River flood control and ecosystem management is also of interest, although there is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. Utilizing annual maximum- and minimum-week runoff as metrics of acute runoff events of, respectively (figure 36), it appears that projected trend in annual maximum-week runoff may vary by subbasin. For example, results for northwestern subbasins (e.g., Missouri River at Canyon Ferry, Milk River at Nashua) indicate annual maximum-week runoff increases slightly through the 21st century. Results for southwestern subbasins (e.g., South Fork Platte River near Sterling) indicate slight decreases in annual maximum-week. Results for annual minimum-week runoff also vary across the subbasins. Annual minimum-week runoff for the northern fringe (Milk River at Nashua) is projected to increase, whereas the western and southwestern fringe (Missouri River at Canyon Ferry, South Fork Platte River near Sterling) may decrease slightly. Such results suggest that future hydroclimate conditions may produce weekly acute runoff events that differ from those experienced in the past. This could affect approaches to reservoir operations to satisfy flood control, water supply, river ecosystem management,

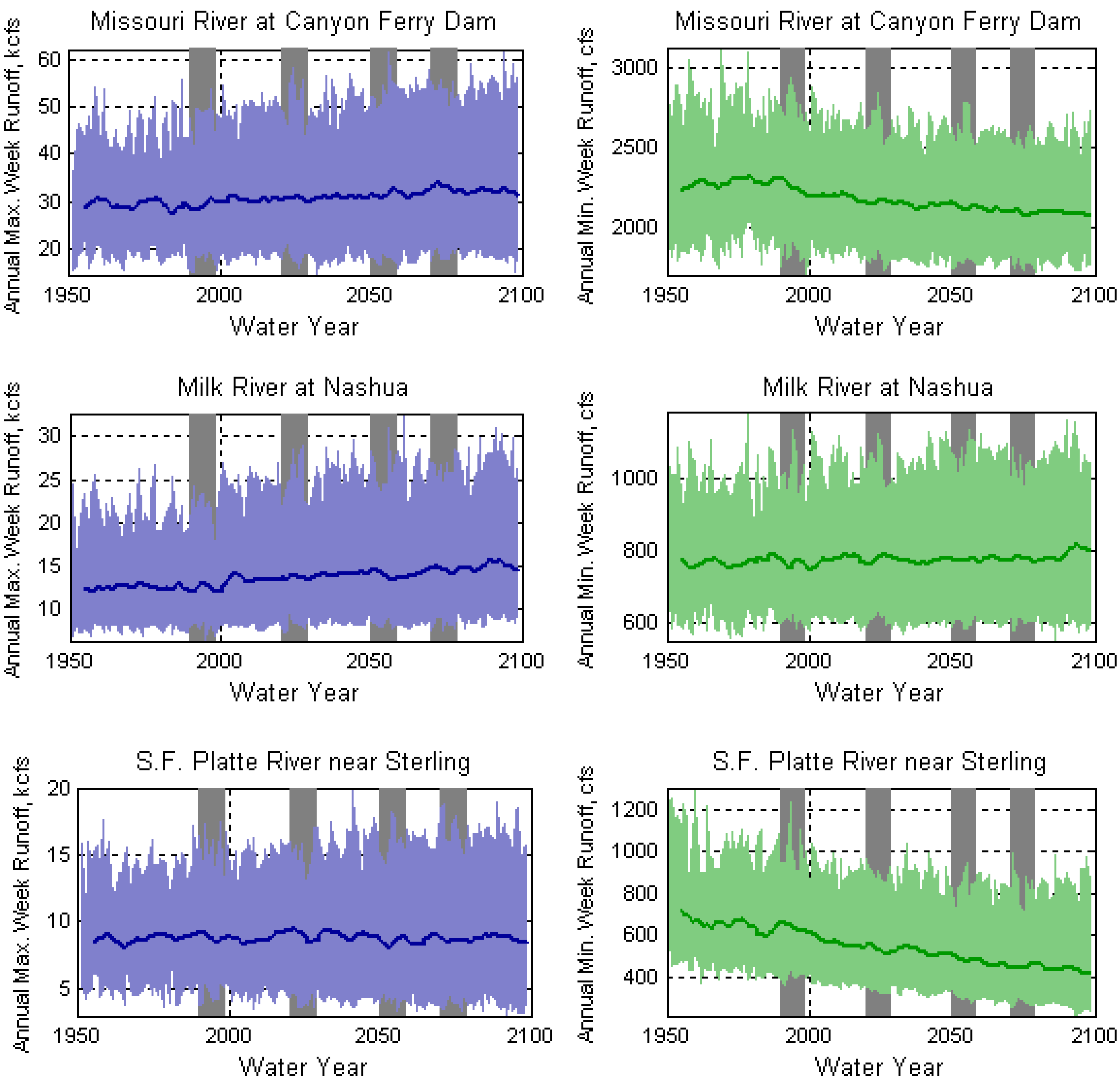


Figure 36. Simulated annual maximum and minimum week runoff for several subbasins in the Missouri River basin.

Figure 36 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative rather than quantitative analysis.

and other objectives dependent on acute runoff possibilities. However, in spite of these findings, it is noted that to understand potential changes in acute runoff events such as these and implications of such changes for reservoir management in the Missouri River basin, more indepth analyses are warranted.

A summary of climate and hydrologic changes is provided in table 4 for four subbasins of the Missouri River basin: Missouri River at Canyon Ferry, Milk River at Nashua, South Fork Platte River near Sterling, and Missouri River at Omaha. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

5.4.2 Other Studies of Future Climate and Hydrology in the Missouri River Basin

Results from Reclamation (2011a) are broadly consistent with findings from previous studies on climate change and hydrologic impacts over the basin. It's important to note that, as the assumed climate changes vary among these studies, so do the associated operations impacts. Under a scenario with doubled carbon dioxide concentrations, Giorgi et al. (1998) suggest area-averaged warming of about 4–6 °C (7.2–10.8 °F) with maximum values occurring in late winter and early spring. Within the study, regionally averaged precipitation generally increased and ranged from 6% in summer to 24% in spring. However, precipitation exhibited significant month-to-month and spatial variability in both magnitude and sign. Also within a double carbon dioxide climate scenario, the Black Hills of South Dakota and Wyoming may experience a 4.6 °C (8.28 °F) average annual increase in temperature and an increase in precipitation of 24% (Giorgi et al. 1994). Another study suggests that temperatures may increase by 4.8 °C (8.64 °F) during winter and by 3.8 °C (6.84 °F) during summer within a double carbon dioxide climate scenario in the Wind River basin (Stonefelt et al. 2000), with precipitation increasing, on average, by 0.5 millimeters per day (mm/day) (0.02 inch per day [in/day]) in winter and by 0.1 mm/day (0.004 in/day) during summer.

An assessment of future climate information over the State of Colorado (Ray et al. 2008) suggests that eastern Colorado may warm as much as 2.5 °F by 2025 relative to a 1950–1999 baseline and by 4 °F by 2050. Summers are projected to warm more than winters with typical summer temperatures in 2050 as warm as the hottest 10% of baseline summers. Projections for the winter indicate fewer extreme cold months, more extreme warm months, and more strings of consecutive warm winters. Model projections generally do not agree whether precipitation will increase or decrease but do indicate a seasonal shift in

Table 4. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Missouri River basin

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Missouri River at Canyon Ferry			
Mean Annual Temperature (°F)	1.6	3.4	4.8
Mean Annual Precipitation (%)	1.9	4.5	6.6
Mean April 1st Snow Water Equivalent (%)	-24.5	-37.6	-49.0
Mean Annual Runoff (%)	0.8	2.1	6.2
Mean December–March Runoff (%)	4.2	13.6	28.4
Mean April–July Runoff (%)	0.4	1.8	3.6
Mean Annual Maximum Week Runoff (%)	4.5	7.6	12.5
Mean Annual Minimum Week Runoff (%)	-4.1	-5.4	-7.2
Milk River at Nashua, Montana			
Mean Annual Temperature (°F)	1.4	3.3	4.6
Mean Annual Precipitation (%)	2.8	7.3	7.9
Mean April 1st Snow Water Equivalent (%)	-74.0	-75.0	-83.0
Mean Annual Runoff (%)	8.2	8.5	12.9
Mean December–March Runoff (%)	11.9	20.1	32.5
Mean April–July Runoff (%)	7.6	8.2	10.6
Mean Annual Maximum Week Runoff (%)	9.8	12.7	17.3
Mean Annual Minimum Week Runoff (%)	1.7	1.0	1.4
South Platte River near Sterling, Colorado			
Mean Annual Temperature (°F)	1.8	3.6	5.0
Mean Annual Precipitation (%)	0.0	0.6	2.1
Mean April 1st Snow Water Equivalent (%)	-59.9	-72.1	-74.7
Mean Annual Runoff (%)	-8.5	-13.9	-17.5
Mean December–March Runoff (%)	-7.8	-12.2	-11.4
Mean April–July Runoff (%)	-7.2	-10.8	-9.9
Mean Annual Maximum Week Runoff (%)	1.8	-3.4	-2.3
Mean Annual Minimum Week Runoff (%)	-16.3	-23.5	-29.3
Missouri River at Omaha			
Mean Annual Temperature (°F)	1.6	3.5	4.8
Mean Annual Precipitation (%)	3.4	6.6	8.5
Mean April 1st Snow Water Equivalent (%)	-76.3	-80.7	-84.5
Mean Annual Runoff (%)	3.7	9.7	12.6
Mean December–March Runoff (%)	5.2	13.0	19.6
Mean April–July Runoff (%)	5.5	12.3	15.1
Mean Annual Maximum Week Runoff (%)	5.9	12.8	15.6
Mean Annual Minimum Week Runoff (%)	-0.7	1.3	1.1

precipitation. Projections also indicate a significant decline in lower-elevation snowpack. Modest declines in snowpack are expected for higher elevations with timing of runoff expected to shift earlier in spring.

There have been relatively fewer studies focused on the Missouri River basin for hydrologic changes relative to others presented in this report (e.g., Columbia, Colorado, and California's Sacramento-San Joaquin Valley). However, one assessment that explored the sensitivity of Missouri River water resources to climate change focused on the effects of potential warming (Lettenmaier et al. 1999). Results show that snow accumulation, while important on the western headwaters of the basin, contributes only a modest portion toward total system runoff. More importantly, the study found that reduced precipitation combined with increasing potential evapotranspiration plays a major role in system runoff reductions.

Another study focused on hydrologic responses to climate change in the Black Hills of South Dakota and Wyoming (Fontaine et al. 2001). Using a variety of climate change scenarios, the study suggests a wide range of potential change in water yield. Within this range, the scenario producing the least impact resulted in reduced yield of almost 10%. Reducing yield of 10% could represent a significant change in average annual streamflow conditions.

Focusing on seasonal yields, the Stone et al. (2001) report results suggests that, in northern and northwestern portions of the basin, yields are projected to increase. Much of the southwestern basin likely is to experience decreases in water yield. This same study found that flows are expected to increase in the upper Missouri, Yellowstone, mainstem Platte, and Cheyenne Rivers while decreasing in the lower Missouri and Kansas Rivers. An early study by Rosenberg (1993) concluded if the “dust-bowl” climate returned to the Great Plains, flows from the Missouri and Upper Mississippi Rivers would be reduced by 28%.

5.5 Future Implications for Water and Environmental Resources

5.5.1 Water Supply, Reservoir Operations and Flood Management

Based on current reservoir operational constraints (e.g., storage capacity, constraints on reservoir water releases to satisfy various obligations), the projected effects of warming without precipitation change over the Missouri River basin would lead to increased watershed evapotranspiration, decreased spring snowpack and snowmelt, and ultimately reduced water supplies to manage under current system and operating conditions.

The preceding section introduced the study by Lettenmaier et al. (1999), which considered multiple climate change scenarios suggesting that the Missouri River basin may experience generally warmer and reduced precipitation conditions (where the latter appears to be a less likely outcome than wetter conditions, based on current precipitation projections summarized in section 5.4.1). These temperature and precipitation change scenarios lead to decreases in snow accumulation. However, when such hydrologic effects were assessed in the context of reservoir system operations along the Missouri River mainstem, the study indicates only slight declines in system water supply yield, suggesting that, while snowpack may be an important factor affecting water supplies in the western headwater basins; it contributes only a modest portion of total system supplies. The water resources impacts analysis reported in Lettenmaier et al. (1999) also suggested that such hydroclimatic changes would lead to declines in basin hydropower generation and moderate decreases in local municipal and industrial (M&I) water supplies. Little effect on recreation was found under the climate change scenarios considered. Adverse navigation impacts were found in some of the scenarios. On managing for system flood risk, Lettenmier et al. (1999) reported improved flood control conditions for the Missouri River system under certain climate change scenarios where flood risk is driven by monthly to seasonal phenomenon rather than storm or storm pattern occurrences. More analysis is required to identify the spectrum of seasonal to acute runoff events relevant to current flood control operations, how these runoff events may change during the 21st century, and how current operating procedures may or may not be challenged in managing such future events. A framework for estimating flood frequency in the context of climate projection information was applied (Raff et al. 2009) to several basins in the Western United States including the James River.

5.5.2 Hydropower

Electricity demand from hydropower generation and other sources generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

5.5.3 Fish and Wildlife

Projected climate changes likely are to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat. Warmer air and water temperatures could potentially improve habitat for quagga mussels and other invasive species, which, in turn, may additionally impact maintenance of hydraulic structures and increased risk of watershed vegetation disturbances due to increased fire potential. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

If temperature and precipitation trends of the 20th century continue, a steeper west to east gradient in wetness may further shrink wetland acreage in the most productive portion of the prairie pothole region (Millett et al. 2009). Warming in the eastern prairie pothole region may produce a more productive wetland climate; however, significant areas of drained wetlands would need to be restored to offset less-productive conditions in the western prairie pothole region.

A warming climate likely will result in fewer wetlands in the Missouri River basin. Prairie wetlands were found to be more sensitive to changes in temperature than to changes in precipitation, and increased temperature scenarios resulted in wetland drying and declining numbers of ponds and ducks (Sorenson et al. 1998). Large increases in precipitation are necessary to offset even small temperature increases. Wetland size, depth, and vegetation characteristics were found to be more sensitive to increases in temperature rather than increases or decreases in precipitation (Poiani and Johnson 1991).

Primary productivity in temperate grasslands was found to be more responsive to precipitation than to temperature, and changes in primary productivity responding to changes in moisture continued up the food web (Hunt et al. 1991). Changes to primary productivity may affect migratory birds by upsetting migratory timing and habitat and food availability. Increased intensity of summer storms, especially those with large hail, likely would increase avian mortality.

Simulations of 50 years of climate change show losses of soil organic carbon across the entire central Great Plains as a result of increased decomposition rates in response to increased temperature (Burke et al. 1991). Some areas were expected to lose 3% of the total soil carbon pool. Areas with the highest precipitation (and high initial soil organic matter) suffered the largest loss of organic soil carbon. Rising nighttime minimum temperatures and their potential effect on grassland productivity in northeastern Colorado were considered by Alward et al. (1999). Minimum temperatures were projected to increase 0.15 °C (0.27 °F) per year over the previous 23 years. Averages of seasonal minimum temperatures also exhibited significant warming with similar trends in winter, spring, and summer. Annual precipitation exhibited a significant linear increase from 230 mm to 480 mm during the same timeframe. The study indicates that, for each 1-°C (1.8-°F) increase in average spring minimum temperature, above-ground net primary productivity of dominant grasses decreases by nearly one-third. Increased season duration is expected to primarily benefit cool-season plants growing most rapidly early and late in the growing season.

Increases in temperature and reduced precipitation have potential to reactivate significant areas of now stabilized or mostly stabilized sand dunes and sheets in the Great Plains (Muhs and Maat 1993). Some of the areas with the greatest potential increase in dune activity are in central Wyoming, eastern Colorado, and western most Kansas. At least one plant listed as endangered (blowout penstemon) under the Endangered Species Act is a dune-obligate.

5.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

5.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008); and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger increased reliance on ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

About 30% of all ground water withdrawn in the United States comes from the Ogallala Aquifer, with irrigation accounting for 96% of the withdrawals. Aquifer recharge is projected to be reduced under all climate scenarios despite some increases in water yield (Rosenberg et al. 1999). Modest changes in climate were found to decrease recharge to the Missouri River by 17%. Greater increases in temperature would reduce recharge far more. This analysis suggests climate change forced by warming will make aquifer mining even less sustainable.

5.5.6 Water Demands

Potential climate changes to agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures; increased atmospheric carbon dioxide levels; and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Furthermore, these natural system changes must be considered in combination with socioeconomic changes including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Agricultural irrigation is the predominant water demand on Reclamation reservoir systems within the western reaches of the Missouri River basin. Given that the atmosphere's moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, crop water demands respond to atmospheric carbon dioxide ozone and potential evapotranspiration in addition to temperature and precipitation (e.g., Baldocchi and Wong 2006; Bloom 2010). Additionally, agricultural water demand could decrease due to crop failures caused by changes in pests and diseases in the future. Seasonal volume of agricultural water demand could increase if growing seasons become longer and assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century, and it is projected that, by the end of the 21st century, the growing season may be more than 2 weeks longer than that typical of the late 20th century (Gutowski et al. 2008). Another study suggests that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Several local studies have been conducted on potential agricultural demand changes in the Missouri River basin. Winter wheat yields are expected to increase as one travels east through Nebraska under doubled carbon dioxide climate scenarios (Weiss et al. 2003). Grain end-use quality also will increase. While yields increased with increased carbon dioxide, several measures of grain end-use quality decreased (Blumenthal et al. 1996). Decreases were attributed to lower grain nitrogen content. Increased grain yields and decreased nitrogen content with increased carbon dioxide is projected by Thompson and Woodward (1994). Other studies that simulated effects of climate change on agriculture in the central plains show potential for reduced yields of major field crops and potential for agricultural expansion northward.

Climate change could also result in changed demand for instream flow or reservoir release to satisfy other system objectives, including ecosystem support, hydropower generation, municipal and industrial water deliveries, river and reservoir navigation, and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by *i*ndustrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production also could be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on water allocations from year to year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic, land use changes, and other nonclimate factors.

Other consumptive uses associated with agricultural reservoir systems management include reservoir evaporation and losses during water conveyance and onfarm application. These types of system losses can be significant. Reservoir evaporation may increase if warming temperatures override other factors, but other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

6. Basin Report: Rio Grande

6.1 Basin Setting

The Rio Grande basin is located in the Southwestern United States and serves as a source of water for irrigation, domestic, environmental and recreational uses in the States of Colorado, New Mexico, and Texas as well as in Mexico (figure 37). The Rio Grande headwaters are in the San Juan Mountains of southern Colorado. The river flows southward through New Mexico, and then southeastward as it forms the international boundary between Texas and Mexico before ultimately flowing into the Gulf of Mexico. The total river length is 1,896 miles, and it flows through the cities of Albuquerque, Las Cruces, El Paso, and Cuidad Juarez, draining a total of approximately 182,200 square miles. Basin topography varies from the mountains and gorges of the headwaters to the Bosque and high desert of central New Mexico, to deserts and subtropical terrain along the boundary between Texas and Mexico. The focus of this section of the report is with respect to the upper Rio Grande basin.

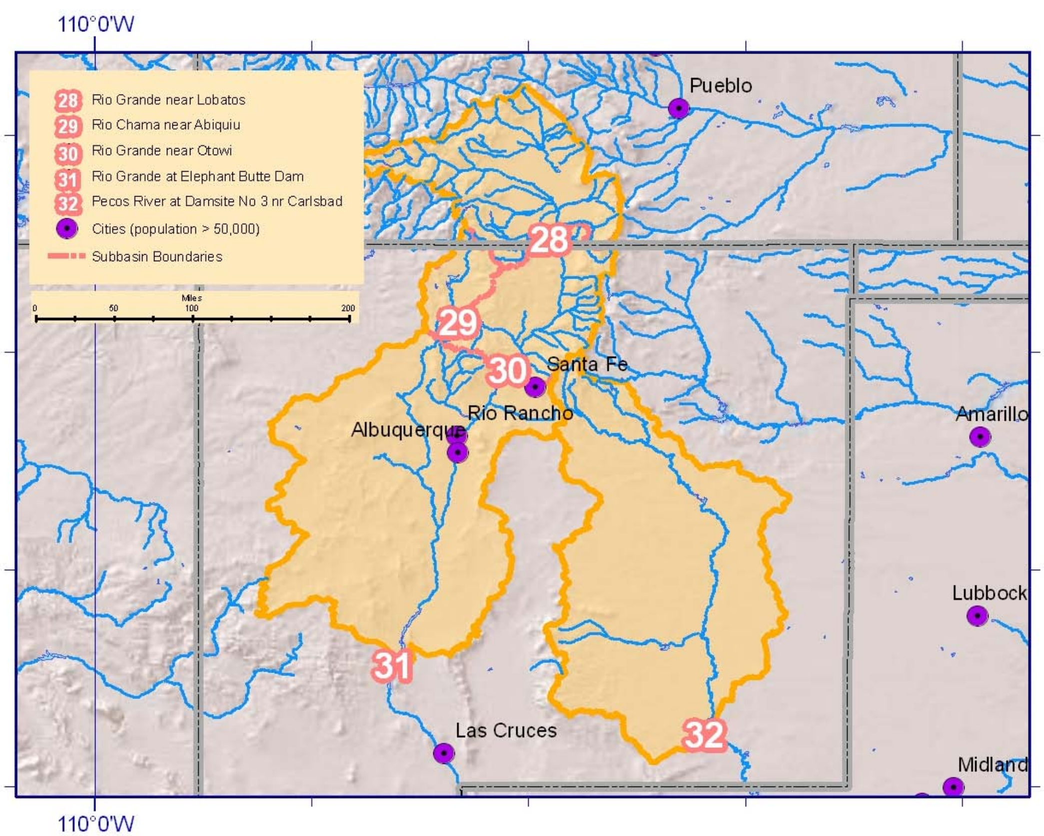


Figure 37. Upper Rio Grande basin, Pecos River basin, and runoff-reporting locations for this report.

The Upper Rio Grande facilities are operated by Reclamation and USACE with input from numerous stakeholders. Water operations staff from both agencies as well as the Middle Rio Grande Conservancy District, U.S. Fish and Wildlife Service, and other interested parties hold daily water operations conference calls during the irrigation season to discuss what water is needed, where it is needed, how it will move through the system, and impacts to the Endangered Species Act- (ESA) listed species. These calls discuss releases by Reclamation from Heron and El Vado Reservoirs in northern New Mexico and releases by USACE at Abiquiu and Cochiti Reservoirs to meet flow needs of the Middle Rio Grande.

Reclamation and USACE work closely with the Middle Rio Grande Collaborative Program that includes 16 Federal, State, and local governmental entities, Indian tribes and pueblos, and nongovernmental organizations representing diverse interests. A 10-year Biological Opinion issued by U.S. Fish and Wildlife Service provides for releases to meet the needs of the ESA-listed silvery minnow. With respect to climate change, Reclamation is currently developing an impact assessment within the WaterSMART Basin Study Program West-Wide Climate Risk Assessments to support identification of impacts from climate change on the resources within the basin. Reclamation will be working with the States to communicate and coordinate this activity.

Climate varies across the Rio Grande basin. Most of the basin is arid or semi-arid, generally receiving less than 10 inches of precipitation per year. In contrast, some of the high mountain headwater areas receive on average over 40 inches of precipitation per year. Most of the total annual flow in the Rio Grande basin results, ultimately, from runoff from mountain snowmelt. Snowmelt processes result in Upper Rio Grande streamflows, from the headwaters to Elephant Butte Reservoir, that peak in the late spring and early summer and diminish rapidly by midsummer. In the reach below Elephant Butte Reservoir and in the Lower Rio Grande, the supply comes directly from storage reservoirs, which may contain water from snowmelt and local inflows in current and past years. The hydrograph in the Lower Rio Grande is, therefore, determined by reservoir operations rather than snowmelt timing and duration. During the summer and fall, monsoon thunderstorms in the central New Mexico and Texas portions of the basin can produce additional peak flows in the river. However, these flows are usually smaller in volume than the snowmelt peaks and also of much shorter duration.

The Rio Grande serves as the primary source of water for agriculture throughout the Rio Grande Valley, as well as the major municipalities along the river corridor. The river also supports unique fisheries and riparian ecosystems along much of its length. The river is heavily utilized, and the river channel size is significantly smaller in the Lower Rio Grande than it is in the Upper Rio Grande. In recent years, intermittent and low flows have occurred in the lower reaches, and river flows do not reach the Gulf of Mexico every year. Along with water quantity, other important issues in the Rio Grande basin include threatened and endangered species and water quality.

The Rio Grande is governed by the Rio Grande Compact, which was approved by Congress in 1939 and serves as an interstate agreement between New Mexico, Colorado, and Texas to equitably apportion the water of the Rio Grande between the three States and the Republic of Mexico.

The Reclamation, USACE, and New Mexico Interstate Stream Commission (NMISC) collectively manage the water facilities in the Upper Rio Grande basin, which comprises the Rio Grande from its headwaters in Colorado through New Mexico to just above Fort Quitman, Texas. Of the 10 total facilities, 5 are located on tributaries: Heron and El Vado Reservoirs operated by Reclamation; Platoro Reservoir operated by a local provider; and Abiquiu and Jemez Canyon Reservoirs operated by the USACE. The remaining five facilities are on the mainstem of the Rio Grande, including the Closed Basin Project operated by Reclamation in Colorado, Cochiti Lake operated by the USACE, and the Low Flow Conveyance Channel (LFCC), Elephant Butte, and Caballo Reservoirs operated by Reclamation. The NMISC is responsible for Rio Grande Compact deliveries to Elephant Butte Reservoir and coordinates with Reclamation and the USACE regarding reservoir operations and accounting of native Rio Grande and San Juan-Chama (SJC) Project contract water.

Two major Reclamation projects exist in the Upper Rio Grande basin: the Rio Grande Project and the Middle Rio Grande Project. The Rio Grande Project, which is located in southern New Mexico and Texas, delivers a water supply for about 178,000 acres of land and electric power for communities and industries. About 60% of these lands receiving water are in New Mexico and the remaining 40% are in Texas. Water also is provided for diversion to Mexico by the International Boundary and Water Commission-United States Section to irrigate about 25,000 acres in the Juarez Valley. The principal crops in the Rio Grande Project are cotton, alfalfa, vegetables, pecans, and grain. The Middle Rio Grande Project extends along the Rio Grande Valley in central New Mexico from Cochiti Dam to Elephant Butte Reservoir and irrigates between 53,000 and 73,000 acres. The Middle Rio Grande Project was jointly planned by Reclamation and the USACE to rehabilitate the Middle Rio Grande Conservancy District facilities (including El Vado Dam located on the Rio Chama and three diversion structures: Angostura, Isleta, and San Acacia) and to control sedimentation and flooding.

The principal crops currently being cultivated in the Middle Rio Grande Project are alfalfa and irrigated pasture.

In the mid-1990s, two species in the Rio Grande basin (the Rio Grande silvery minnow and the southwestern willow flycatcher) were designated as endangered under the Federal Endangered Species Act. A delicate balance in water management in the basin is required to meet species and habitat needs, manage flows in the highly variable flow regime of the Rio Grande, and satisfy competing water demands.

6.2 Historical Climate

Temperature in the Rio Grande basin varies from year to year as well as with topography. Mean annual temperatures increase as elevation decreases as the river flows south from the mountains through the desert in the southern part of the basin. The basin also experiences natural year-to-year variability.

Over the course of the 20th century, warming has been prevalent over the Rio Grande basin. Above Elephant Butte (figure 38), the basin average temperature has increased by approximately 1–2 °F during the course of the 20th century.

The warming of the Rio Grande basin has not been steady in time throughout the 20th century. The basin's average temperature increased steadily from roughly the 1910s to the mid-1940s and then declined slightly until the 1970s before increasing steadily through the end of the century (figure 38, top panel). The warming identified is consistent with other findings within the region. In northern New Mexico, recent annual average temperatures have been more than 2 °F above mid-20th century values (D'Antonio 2006; Rangwala and Miller 2010). In particular, the San Juan Mountains, the headwaters of the Rio Grande, appears to have experienced a 1 ºC increase from 1895–2005 with most of the warming occurring during 1990–2005.

Precipitation in the Rio Grande basin is highly variable; both throughout time as shown in figure 38 and spatially throughout the basin. Most precipitation falls as snow in the mountains in southern Colorado and northern New Mexico; however, summertime precipitation events in the southern portion of the basin also contribute to the total annual precipitation. A slight increase in basin precipitation is evident over the past century (figure 38); however, any change in precipitation appears to be subtle relative to annual variability.

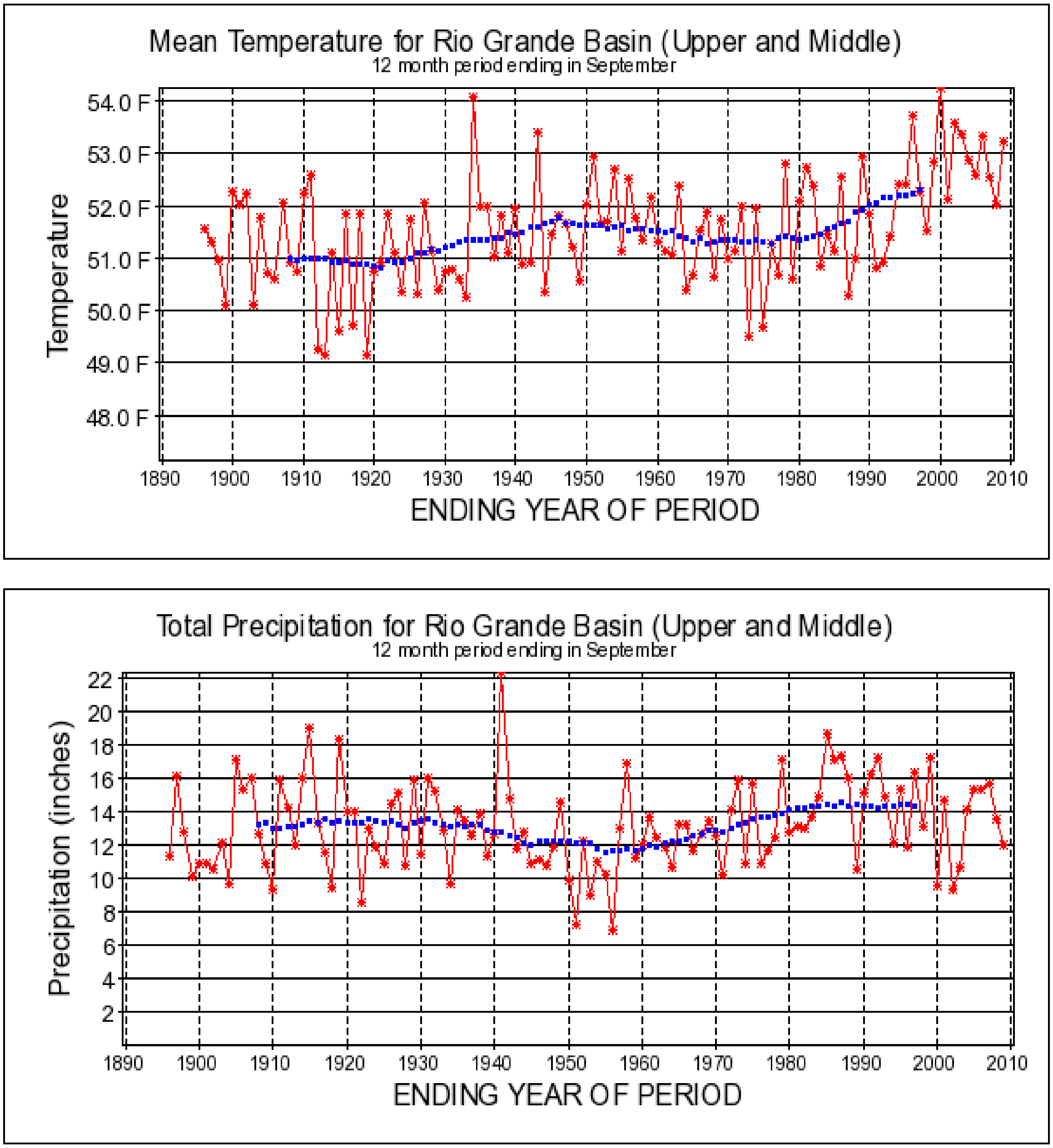


Figure 38. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Rio Grande basin above Elephant Butte.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

6.3 Historical Hydrology

Streamflow in the Rio Grande basin varies significantly from month to month as well as from year to year. The majority of the annual streamflow in the Rio Grande basin comes in spring and early summer as a result of snowmelt. Streamflow is lowest in late summer and fall; however, flows can be temporarily augmented by runoff from localized monsoon precipitation events.

Changes in snowpack in the basin have been studied with results that appear to be sensitive to the time-period analyzed. April 1st SWE increased over the latter half of the century (1950–1999) (Regonda 2005; Mote 2006); however, over the relatively shorter period 1980–2006, April 1st SWE appears to have decreased (Enquist et al. 2008). Changes in April 1st SWE are important to understand because they could be indicative of more precipitation falling as rain and less falling as snow or earlier snowmelt.

If trends in historical runoff within the basin are to be considered, review of historical data shows that some runoff trends may be apparent depending on location and period of record being assessed. However, evaluation of such trends suggests they are relatively weak.[8] Other studies have found trends that are more significant depending on location, period, and runoff aspect considered. For example, the timing and origin of runoff in the Rio Grande basin appears to have been changing over the past century, trending toward earlier springtime snowmelt (Stewart et al. 2005; Enquist et al. 2008) and increased streamflow in winter months (Passell et al. 2004). The timing of peak runoff across northern New Mexico over the past half century occurred on average 7 days earlier when compared with the first half of the century (Stewart et al. 2005; Enquist et al. 2008). In addition, streamflow in the winter months of January, February, and March has increased over the last quarter century relative the century as a whole (Passell et al. 2004). Streamflow reconstructions based on tree rings have suggested that, in terms of annual streamflow volume, the second half of the 20th century was fairly representative of the long-term average hydrology and range of variability, but the period from 1975–2000 is wetter than the long-term average (Lewis and Hathaway 2002).

[8] Trend significance was assessed using statistical testing during the period of 1951–1999 applied to historical simulated runoff results under observed historical weather conditions (Reclamation 2011a). Trends were computed and assessed for four Missouri basin locations, focusing on annual and April–July runoff. In all cases, computed trends were judged to not be statistically significant with 95% confidence.

6.4 Future Changes in Climate and Hydrology

This section summarizes results from studies focused on future climate and hydrologic conditions within the Rio Grande basin. Emphasis in this discussion is placed on the snowmelt-driven Upper Rio Grande. Discussion first focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document.

6.4.1 Projections of Future Climate

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the perspective of basin average and, secondly, as those climate conditions are distributed throughout the basin. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented; and, finally, climate and snowpack changes translated into effects on annual and seasonal runoff as well as acute runoff events relevant to flood control and ecosystems management are discussed.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Rio Grande basin may increase steadily during the 21st century. The basin-average mean-annual temperature is projected to increase by roughly 5–6 °F during the 21st century in the Upper Rio Grande basin. The range of annual possibility widens through time.

The ensemble mean of projections indicates that mean-annual precipitation, averaged over either subbasin presented for the Upper Rio Grande basin (figure 39), may gradually decrease during the 21st century. This is evident by following the ensemble median of the annual precipitation through time for both basins. The projections also suggest that annual precipitation in the Rio Grande basin will remain quite variable over the next century. Despite the previous statement about the ensemble mean, there is significant disagreement among the climate projections regarding change in annual precipitation over the region.

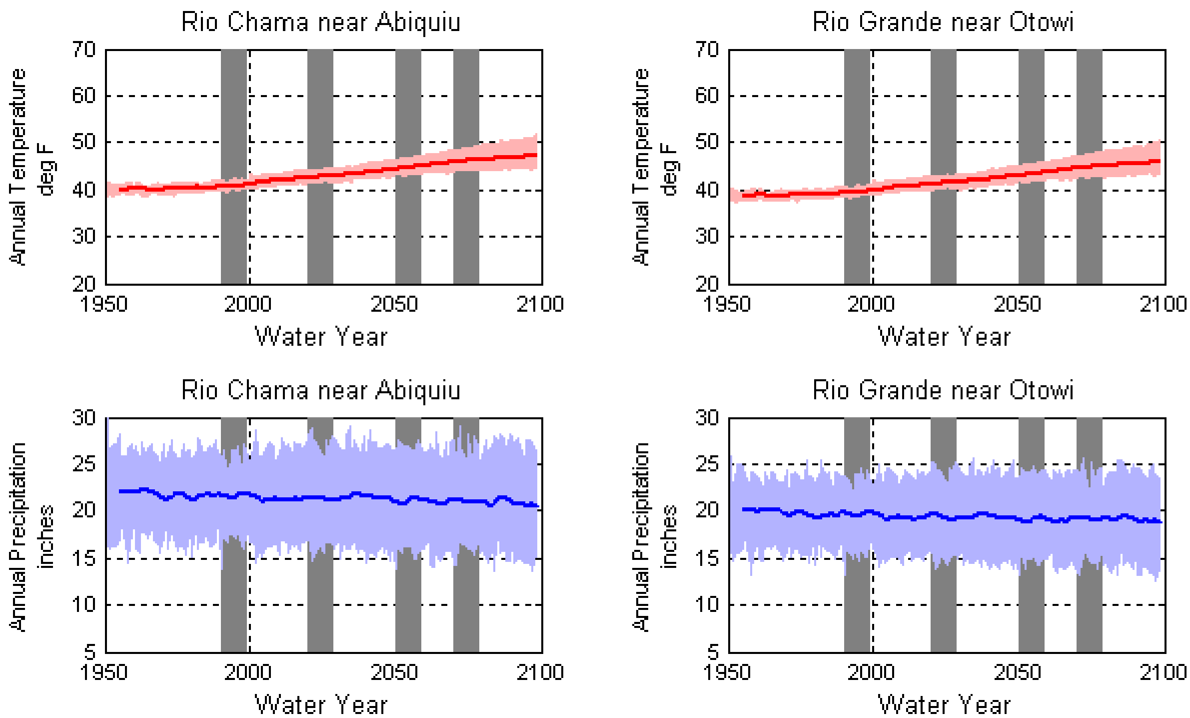


Figure 39. Simulated annual climate averaged over Rio Grande subbasins.

Figure 39 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

Projection of climate change is geographically complex over the upper Rio Grande basin, particularly for precipitation. For example, consider the four decades highlighted on figure 39 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, annual average temperatures are generally cooler in the high-elevation upper reaches in the north and along the mountainous rim (figure 40, top left panel). Warmer temperatures occur to the south and in lower lying areas. Likewise, precipitation is generally greater in the upper reaches along the mountainous rim, and lesser in the lower lying areas and to the south (figure 41, top left panel). Projected temperature changes under projected climate-change scenarios are generally uniform over the basin and steadily increase through time (figure 40). For precipitation, similar geographic

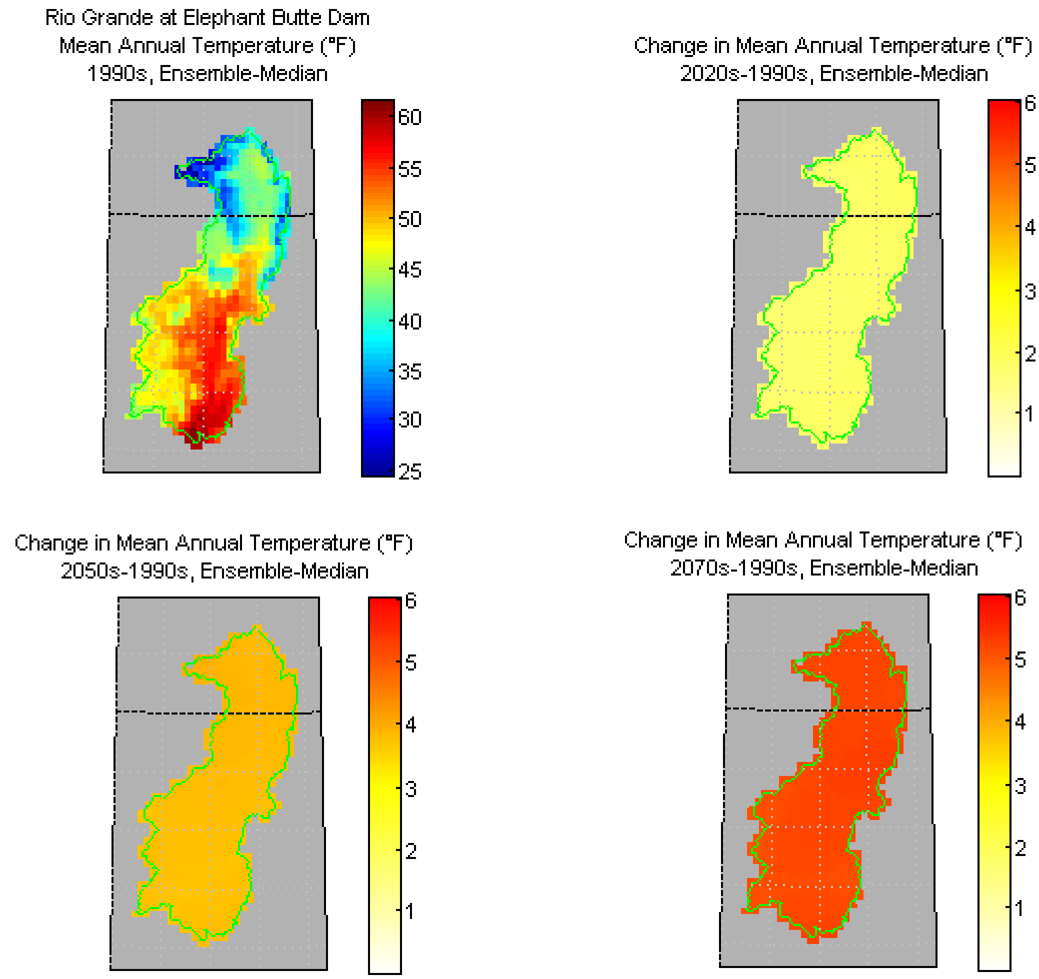


Figure 40. Simulated decade-mean temperature over the Rio Grande basin above Elephant Butte.

Figure 40 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

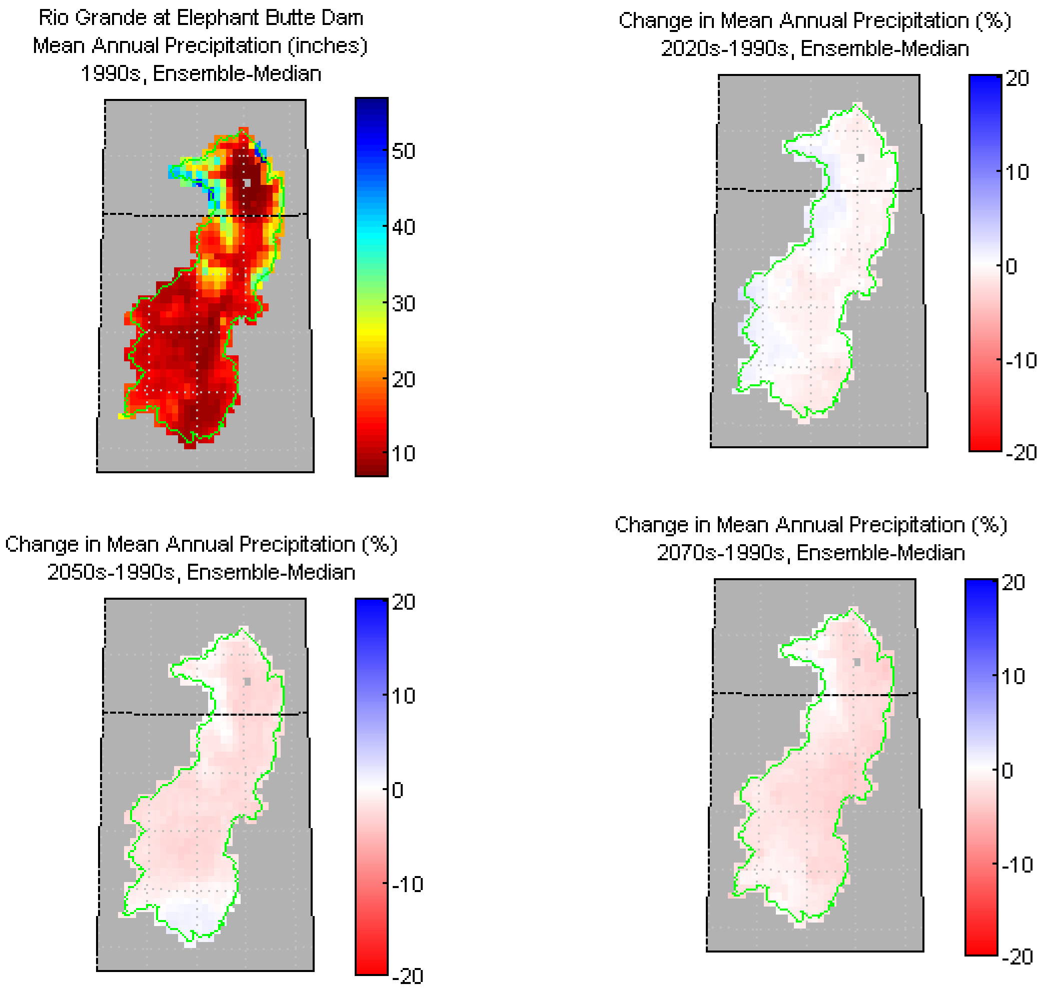


Figure 41. Simulated decade-mean precipitation over the Rio Grande basin above Elephant Butte.

Figure 41 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

consistency is found, although there is less uniformity during the earlier part of the 21st century decades. Overall, precipitation is projected to gradually decline over much of the basin during the course of the 21st century. Despite the overall magnitude of precipitation under increasing temperature projections, the character of precipitation within the Upper Rio Grande basin is expected to change under warming conditions, resulting in more frequent rainfall events and less frequent snowfall events.

Temperature and precipitation changes are expected to affect hydrology in various ways including snowpack development. As noted previously, warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff to the Upper Rio Grande during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify changes in snowpack, it is apparent that the projected warming in the Upper Rio Grande basin tends to dominate projected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 42). Snowpack decreases are expected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. This is particularly the case for the lower lying areas of the basin.

Changes in climate and snowpack within the Upper Rio Grande basin will change the availability of natural water supplies. These changes may be due to annual runoff, and also changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would offset or amplify the effect. Results from Reclamation (2011a) suggest that annual runoff changes are generally consistent but do vary slightly by location in the Upper Rio Grande basin (figure 42), depending on baseline climate and the projected temperature and precipitation changes. For example, annual runoff reductions in the Rio Chama at Abiqiu, draining the northwestern reaches of the basin, are projected to be somewhat less than reductions found at river locations draining the northern and eastern portions of the basin. However, at all locations, decade-mean annual runoff is projected to steadily decline through the 21st century, responding to both slight decreases in precipitation and warming over the region.

The seasonality of runoff is also projected to change in the Upper Rio Grande. Warming would be expected to lead to more rainfall and runoff, rather than snowpack accumulation, during the winter. Conceptually, this change would lead to increases in the December–March runoff and decreases in the April–July

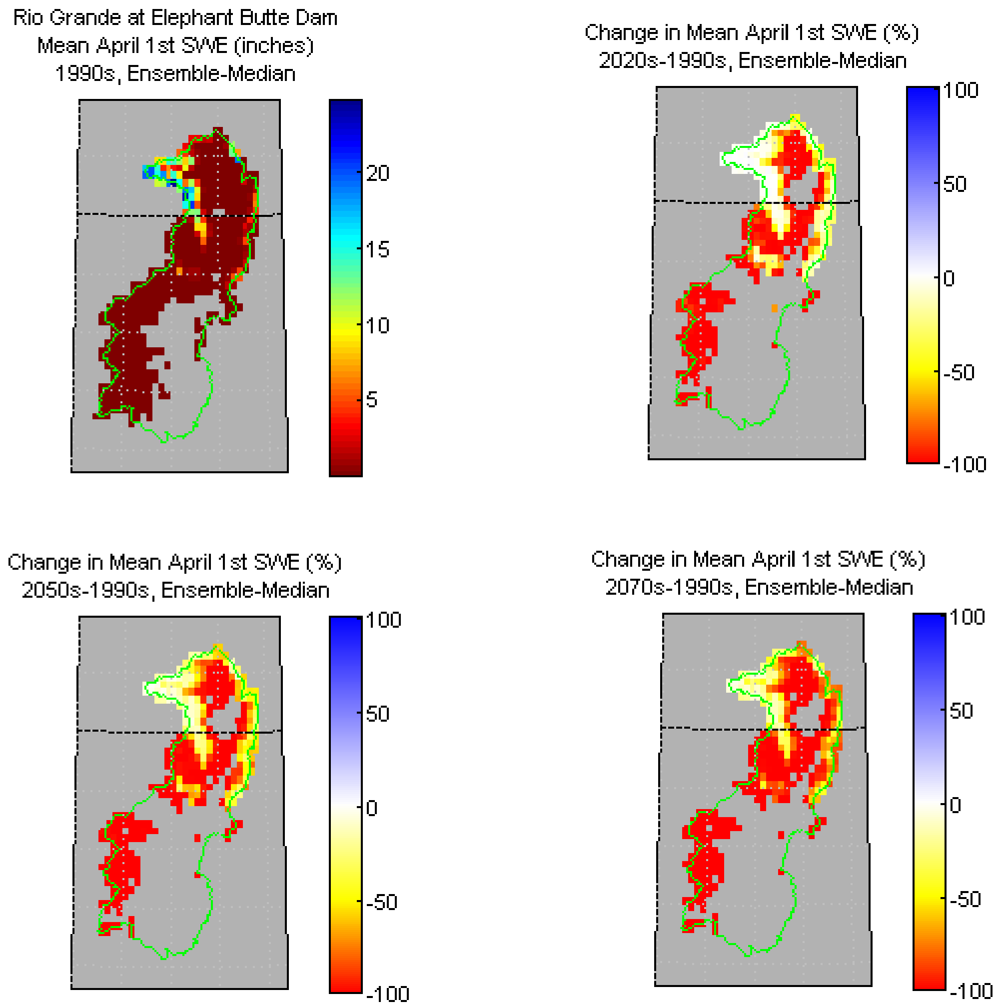


Figure 42. Simulated decade-mean April 1st snowpack over the Rio Grande basin above Elephant Butte.

Figure 42 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

runoff. However, results from across the upper Rio Grande basin suggest that the degree to which this concept is consistent with projections depends on the location of interest (figure 43). The concept is supported by results for the December–March seasonal runoff in the Rio Chama at Abiquiu, as mean seasonal runoff increases for each of the three future decades. However, for the three locations shown on the Rio Grande (Rio Grande at Lobatos, Rio Grande at Lobatos, and Rio Grande at Elephant Butte), mean seasonal runoff changes during December–March generally follow mean annual runoff changes, without this shift from April–July to December–March runoff. However, at all four of the locations shown on figure 43, mean April–July runoff is expected to decline, and these declines are expected to become greater in magnitude over the course of the 21st century. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Changes in the magnitude of flood peaks also are expected in the Upper Rio Grande, although there is less certainty in the analysis of these types of acute events than there is for changes in annual or seasonal runoff. Annual maximum- and minimum-week runoff, as metrics of acute runoff events (figure 44), indicate that annual maximum-week runoff may gradually decline during the 21st century. Results are generally consistent across the subbasins shown. These results suggest that future flood events in the Rio Grande may be smaller in magnitude than those experienced in the 1990s, although the streamflow variability is expected to continue to be large. These changes have implications for flood control and ecosystem management. However, it is important to note that there is a high degree of variability among model simulations suggesting there is a high degree of uncertainty in this flood metric.

For annual minimum-week runoff, similar consistency is found across the subbasins, also showing projected declines during the 21st century. These results suggest that future low flow periods in the Rio Grande may be drier still looking into the future. Decreasing annual minimum runoff may reduce available diversions for agricultural, municipal, and industrial uses. Decreasing minimum runoff also adversely affects aquatic habitats through reduced wetted stream

perimeters and availability of aquatic habitat and through increased water temperatures detrimental to temperature-sensitive aquatic organisms. However, there is a high degree of variability among model simulations suggesting there is a high degree of uncertainty in this low flow metric. Nevertheless, nearly all ensemble members project an overall decrease in low flow values, and the uncertainty lies in the magnitude of this trend.

A summary of climate and hydrologic changes is provided in table 5 for three subbasins of the Upper Rio Grande basin: Rio Chama at Abiquiu, Rio Grande near Otowi, and Rio Grande at Elephant Butte Dam. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

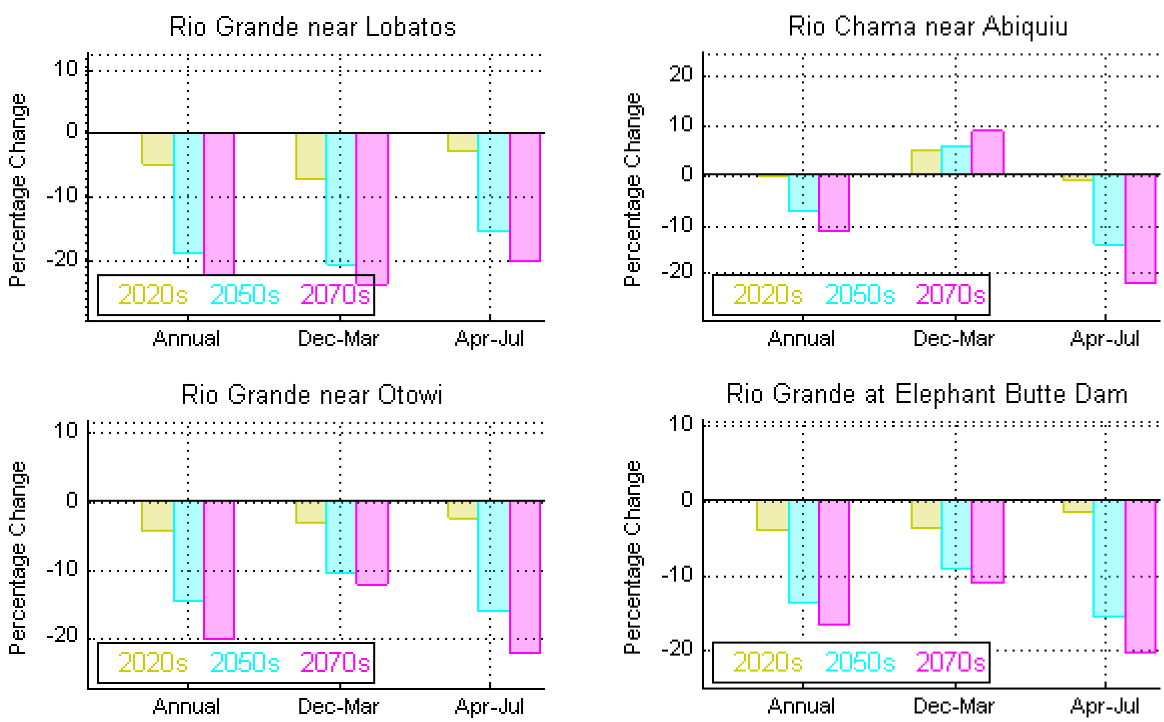


Figure 43. Simulated changes in decade-mean runoff for several subbasins in the Rio Grande basin.

Figure 43 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

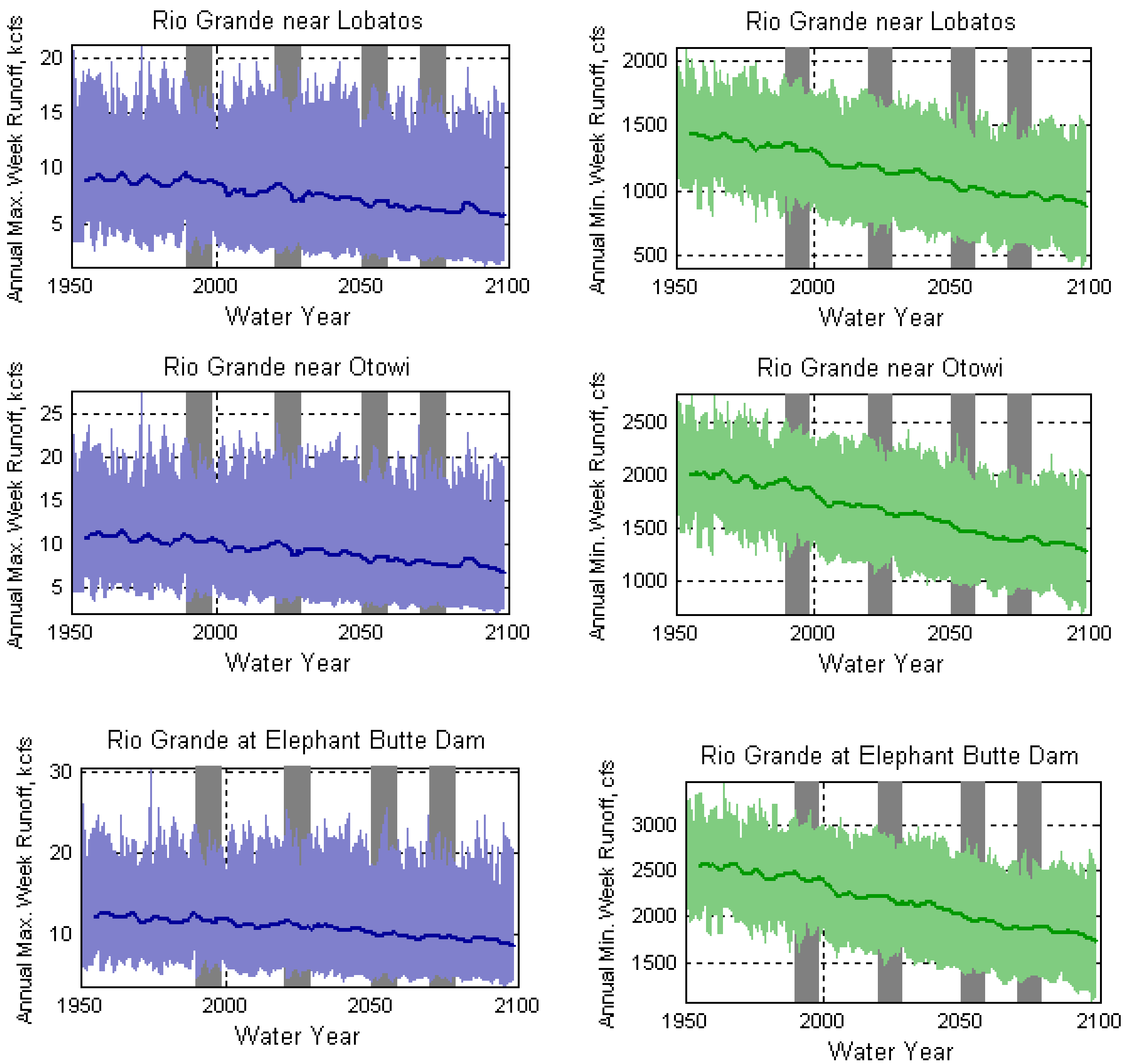


Figure 44. Simulated annual maximum and minimum week runoff for several subbasins in the Rio Grande River basin.

Figure 44 displays the ensemble of annual "maximum 7-day" and "minimum 7-day" runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

Table 5. Summary of Simulated Changes in Decadal Hydroclimate for several subbasins in the Rio Grande basin

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Rio Chama near Abiquiu			
Mean Annual Temperature (°F)	1.9	3.8	5.3
Mean Annual Precipitation (%)	-1.1	-2.3	-2.5
Mean April 1st Snow Water Equivalent (%)	-47.6	-61.4	-68.2
Mean Annual Runoff (%)	-0.2	-7.3	-11.0
Mean December–March Runoff (%)	4.8	5.5	8.6
Mean April–July Runoff (%)	-1.3	-13.9	-21.7
Mean Annual Maximum Week Runoff (%)	-4.3	-9.5	-14.9
Mean Annual Minimum Week Runoff (%)	-12.1	-19.2	-23.9
Rio Grande near Otowi			
Mean Annual Temperature (°F)	1.9	3.7	5.2
Mean Annual Precipitation (%)	-1.5	-2.5	-2.4
Mean April 1st Snow Water Equivalent (%)	-48.5	-63.8	-72.9
Mean Annual Runoff (%)	-4.4	-14.4	-19.9
Mean December–March Runoff (%)	-3.1	-10.4	-12.0
Mean April–July Runoff (%)	-2.5	-15.9	-21.8
Mean Annual Maximum Week Runoff (%)	-9.3	-20.3	-25.3
Mean Annual Minimum Week Runoff (%)	-11.7	-21.6	-26.3
Rio Grande at Elephant Butte Dam			
Mean Annual Temperature (°F)	1.9	3.7	5.1
Mean Annual Precipitation (%)	-0.9	-2.3	-1.9
Mean April 1st Snow Water Equivalent (%)	-72.4	-80.7	-85.3
Mean Annual Runoff (%)	-4.1	-13.5	-16.4
Mean December–March Runoff (%)	-3.6	-8.9	-10.9
Mean April–July Runoff (%)	-1.6	-15.4	-20.0
Mean Annual Maximum Week Runoff (%)	-6.1	-15.7	-18.8
Mean Annual Minimum Week Runoff (%)	-9.6	-18.2	-22.4

6.4.2 Other Studies

Results from Reclamation (2011a) are broadly consistent with previous studies on climate change and hydrologic impacts over the basin. One study reports that the projected mean-annual temperatures over New Mexico may increase 3.3 °C (5.94 °F) by 2061–2090 compared to the 1971–2000 average, based on a multimodel average (D'Antonio 2006). This study went further to report that drastic reductions in Rio Grande runoff by the end of the 21st century are likely. Another study is consistent and considered a range of future climate scenarios and estimated that average reductions in Rio Grande flow could range from 3.5–13.7% in 2030 and 8.3–28.7% in 2080 relative to the baseline period 1971–2000 (Hurd and Coonrod 2007).

6.5 Future Implications for Water and Environmental Resources

6.5.1 Water Supply, Reservoir Operations and Flood Management

Warming without precipitation change over the Rio Grande basin likely would lead to increased watershed evapotranspiration, decreased spring snowpack and snowmelt, and ultimately reduced water supplies to manage under current system and operating conditions. Current climate projections suggest that precipitation could slightly decrease over the basin during the 21st century, which would amplify water supply reductions under warming alone. Other potential warming impacts could affect supplies, including increased reservoir and stream evaporation and runoff effects from ecosystem changes (e.g., pine beetle infestation).

Based on current reservoir operations constraints (e.g., capacity, flood control rules) shifts in seasonal runoff likely would lead to reduced water supplies. This expectation is based on current operating conditions that limit storage opportunities during the winter runoff controlled by flood control considerations at basin reservoirs and that increased winter runoff under climate change will not necessarily translate into increased storage of water leading into the spring season. Capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

Changes in runoff characteristics also influence flood control considerations. Projected increases in winter runoff volumes in the Rio Chama likely will result in increased reservoir inflow to manage during the winter season. Increased winter time reservoir inflows could motivate adjustments to flood control strategies (e.g., Brekke et al. 2009 and Lee et al. 2009) at Heron, El Vado, Abiquiu, and Cochiti Reservoirs and potentially reservoirs lower down in the system. For example, given existing reservoir capacities and current flood control rules (e.g., winter draft period, spring refill date), a pattern of more winter runoff in the Rio Chama system might lead to increased flooding risk. If current flood protection risks are to be preserved, it could become necessary to modify infrastructure to preserve flood protection performance and/or make flood control rule adjustments as climate evolves (e.g., deeper winter draft requirements), which may further affect dry season water supplies (e.g., spring refill beginning with less winter carryover storage). However, changes in the magnitude of maximum week flows also are evaluated in this chapter, with projections showing gradual decline in this flood-related metric. It remains to be determined whether changes in seasonal runoff timing within the Rio Chama or changes in acute events would have a more significant effect on flood control. More analysis is required to identify the spectrum of seasonal to acute runoff events relevant to current flood control operations, how these runoff events may change during the 21st century, and how current operating procedures may or may not be challenged in managing such future events.

6.5.2 Hydropower

Electricity demand, from hydropower generation and other sources, generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

The warming projected across the Rio Grande basin could lead to decreased energy demand during winter and increased demand during summer; however, based on the findings of Scott and Huang (2007), the net effects of on total energy demand are projected to be modest (±5% per 1.8 °F). Such demand changes might motivate adjustments to reservoir operations for hydropower objectives (e.g., less winter production, more summer production), which may not be consistent with runoff impacts and/or potential flood control adjustments (e.g., more winter release, less summer release).

It is noted that power generation fluctuates in the Rio Grande basin both seasonally and annually. Because reservoirs in the Rio Grande basin typically generate power incident to other reservoir releases, changes in annual runoff may be more significant to hydropower generation than changes in seasonal runoff patterns.

6.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). In New Mexico's Rio Grande basin, reduced snowpack, earlier runoff, and higher evaporative demands due to climate change will affect vegetative cover and species' habitat (Hurd and Coonrod 2007). At present, most projected impacts primarily are associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat. Warmer air and water temperatures could potentially make habitat more favorable for quagga mussels and other invasive species that, in turn, may additionally impact maintenance of hydraulic structures. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change can also trigger synergistic effects in ecosystems and exacerbate invasive species problems.

6.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

6.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger increased reliance on ground water resources. However, warmer wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

The Upper Rio Grande basin has been heavily reliant on ground water for municipal supply and to augment river flows for environmental purposes; in the Rio Grande Project, ground water also is used to augment surface water supplies for agriculture. As the climate in the Rio Grande basin warms and evaporation increases and runoff decreases, natural ground water recharge will likely diminish. Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on ground water resources. However, it is also possible that warmer, wetter winters could increase the amount of water available for ground water recharge during that time in the Rio Grande basin. It has not been demonstrated how much of this additional winter runoff can be captured and utilized without the use of artificial recharge schemes.

6.5.6 Water Demands

Potential climate changes to agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures; increased atmospheric carbon dioxide levels; and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Furthermore, these natural system changes must be considered in combination with socioeconomic changes including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Agricultural irrigation is the predominant water demand in the Rio Grande basin and the Western United States as a whole. Given that the atmosphere’s moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, crop water demands respond to atmospheric carbon dioxide ozone and potential evapotranspiration in addition to temperature and precipitation (e.g., Baldocchi and Wong 2006; Bloom 2010). Additionally, agricultural water demand could decrease due to crop failures caused by changes in pests and diseases in the future. Seasonal volume of agricultural water demand could increase if growing seasons become longer, assuming that farmers could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it may be more than 2 weeks longer than the length typical of the late 20th century (Gutowski et al. 2008). Another study suggests that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands may also increase significantly (Pacific Institute 2009).

Although changes in water demands associated with natural processes may be difficult to quantify, municipal and industrial consumption increases associated with population growth will occur. Domestic water use is not very sensitive to changes in temperature and precipitation (Frederick 1997), and water conservation measures may offset potential increases in per capita water usage. Although the use of new water efficient appliances and fixtures will increase through institutional measures and mandates, socioeconomic factors will impact water conservation.

Climate change also could result in changed demand for instream flow or reservoir release to satisfy other system objectives, including ecosystem support, hydropower generation, municipal and industrial water deliveries, river and reservoir navigation, and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing). Diversions and consumptive use by industrial cooling facilities are predicted to increase since these processes will function less efficiently with warmer air and water temperatures. The timing of these diversions and those for hydropower production also could be a factor in ecosystem demands and navigation and recreational water uses.

As climate change might affect water supplies and reservoir operations, the resultant effects on water allocations from year to year could trigger changes in water use (e.g., crop types, cropping dates, environmental flow targets, transfers among different uses, hydropower production, and recreation). Such climate-related changes in water use would interact with market influences on agribusiness and energy management, demographic, land use changes, and other nonclimate factors.

Other consumptive uses associated with agricultural reservoir systems management include reservoir evaporation and losses during water conveyance and onfarm application. These types of system losses can be significant. Though intuitively one might expect increased evaporation with increased temperature, changes in other factors affecting surface energy balance (e.g., net radiation and wind speed) may not be congruous with the notion of increasing air temperatures. Historical potential evapotranspiration data typically are limited and inconsistent. Consequently, there is uncertainty about how physically driven agricultural water demands may change under climate change. Also, although reservoir evaporation may increase if warming temperatures override other factors, other agricultural losses may be reduced in the future with more efficient application methods and conveyance improvements.

7. Basin Report: Sacramento and San Joaquin

7.1 Basin Setting

The Sacramento and San Joaquin Rivers are located in the Central Valley of California. Sometimes referred to as the Great Valley, it is a large north to south trending alluvial basin extending over 450 miles from the southern Cascade Mountains near the city of Redding to the Tahachupi Mountains south of the city of Bakersfield. The basin is about 40 to 60 miles wide and is bounded by the Coast Range to the west and the Sierra Nevada Mountains on the east. Hydrologically, the Central Valley is divided into three hydrographic regions including the Sacramento, San Joaquin and Tulare Lake basins (figure 45).

Figure 45. Sacramento River, San Joaquin River, Tulare basin, and runoff-reporting locations for this report.

The Sacramento River drains the northern portion and the San Joaquin drains the central and southern portions of the Central Valley. Both of these rivers flow into the Sacramento-San Joaquin Delta (Delta). This region is the largest estuary on the west coast of the United States. Typically, the Tulare Lake basin is internally drained. However, in some wetter than normal years, flow from the Tulare Lake region reaches the San Joaquin River. Together, the Sacramento and San Joaquin Rivers drain an area of approximately 59,000 square miles.

The Sacramento River is the largest river in California with an historic mean annual flow of 22 million acre-feet. It drains an area of about 27,000 square miles. The Sacramento River arises in the volcanic plateaus of northern California where it is joined by the Pit River above Shasta Dam, a Reclamation facility. Below Shasta Dam, transmountain diversions from the Trinity River (tributary to the Klamath River) along with many small- and moderate-sized tributaries join the river as it flows south through the Sacramento Valley. Major tributaries also join the river from the east including the Feather, Yuba, and American Rivers. Major facilities on these rivers include Oroville Dam operated by the California State Water Project on the Feather River and Folsom Dam operated by Reclamation on the American River. After a journey of over 400 miles, the river reaches Suisun Bay in the Sacramento-San Joaquin Delta before discharging into San Francisco Bay and the Pacific Ocean.

The San Joaquin River is the second largest river in California with an historic mean annual flow of 7.5 million acre-feet. It drains an area of 32,000 square miles. The San Joaquin originates in the high Sierra Nevada Mountains in east-central California. The river initially flows westward reaching Friant Dam, a Reclamation facility, before entering the San Joaquin Valley. At Friant Dam, diversions are made to the Friant Division of the Central Valley Project, which is primarily located in the Tulare Lake basin. Prior to implementation of the San Joaquin Restoration Program, flows below the dam were minimal except during flood conditions. Releases from the dam flow initially westward until reaching the Chowchilla Bypass (a constructed flood control facility) or the Mendota Pool (a managed irrigation water control facility). From there, the river turns northward and begins receiving returns flows from agricultural and wildlife refuge areas upstream of its confluence with the Merced River, a major tributary. As the river continues northward, it receives inflows from several eastside tributaries including the Toulumne, Stanislaus, Calaveras, and Mokelumne Rivers, each of which have major dams that store water and regulate flows. After a distance of 330 miles, the San Joaquin joins the Sacramento River near Suisun Bay in the Sacramento-San Joaquin Delta.

Reclamation's major role in the Central Valley began in 1933 with the construction of the Central Valley Project (CVP). Today the CVP consists of 20 dams, 11 powerplants, and more than 500 miles of canals that serve many purposes including providing, on average, 5 million acre-feet of water per year to irrigate approximately 3 million acres of land in the Sacramento, San Joaquin, and Tulare Lake basins, 600,000 acre-feet per year of water for urban users, and 800,000 acre-feet of annual supplies for environmental purposes.

In the Sacramento River basin, CVP and State Water Project (SWP) must coordinate releases of water from reservoirs to maintain flows within acceptable ranges to meet multiple regulatory requirements for water quality and endangered species habitat conditions in the Sacramento River and Sacramento-San Joaquin Delta. The management required to meet specific flow requirements for the CVP and SWP established in the Coordinated Operations Agreement (COA) is accomplished by Reclamation and California Department of Water Resources (DWR) personnel working together at the shared Joint Operations Center (JOC) facility in Sacramento. The coordination of operations by Reclamation, DWR, and National Weather Service (NWS) is also essential to managing flood risks during periods of high runoff. The sharing of water supply and runoff forecasts between Reclamation, DWR, NWS, and CVP/SWP contractors is important to developing coordinated water supply allocations and reservoir operations plans.

Water delivery to contractors is another example of the high degree of on-the-ground coordination that occurs in CVP and SWP operations. San Luis Reservoir (SLR), a major off-stream storage facility, is jointly owned and operated by DWR and Reclamation. At times, Reclamation receives assistance in storing water in SLR from DWR through using the SWP's Banks pumping facility and conveyance in the California Aqueduct. Reclamation recently has begun construction on a facility that will provide addition conveyance flexibility through a physical intertie between CVP's Delta-Mendota Canal and SWP's California Aqueduct. In the Tulare Lake basin, some CVP and SWP contractors receive water by conveyance through the California Aqueduct and the Cross Valley Canal shared facilities.

The California Federal Ecosystem Directorate (CALFED) Ops group was established through the CALFED Framework Agreement. The CALFED Ops group is responsible to coordinate CVP and SWP operations with the requirements of the State Water Resources Control Board's Decision 95-6, the biological opinions for the Delta smelt and winter-run salmon, and the Central Valley Project Improvement Act. The agencies participating in this group include DWR, California Department of Fish and Game (DFG), State Water Resources Control Board (SWRCB), U.S. Fish and Wildlife Service, NWS, EPA, and

Reclamation. The Ops group decisions can involve change in Delta export rates, barrier operations, or reservoir releases that do not conflict with other operational constraints such as flood control operations, water quality parameters, or permit constraints and are intended to have no net water supply costs.

With respect to the impacts of climate change, the Mid-Pacific Region recently has begun coordinating with a wide range of Federal, State, and local agencies and stakeholder groups through participation in California Landscape Conservation Cooperative on applied science for effective resource management opportunities in the region. Future coordination through participation in the Great Basin and North Pacific Landscape Conservation Cooperatives is anticipated to occur in the near future. Additional coordination through participation in the U.S. Department of the Interior Climate Science Centers is similarly beginning.

Reclamation and DWR also are coordinating with respect to planning for future improvements in the CVP and SWP projects such as the Bay-Delta Conservation Plan. The Central Valley Project Improvement Act (CVPIA) directed Reclamation to assist the State of California in meeting its future water needs and to develop cost effective plans to minimize the adverse effects of the dedication of 800,000 acre-feet of CVP yield to environmental purposes. In responding to this congressional mandate, Reclamation has worked closely with many Federal, State and local agencies as well as numerous stakeholder interest groups. This coordination has occurred at many levels and taken many forms from on-the-ground habitat restoration projects to developing ecosystem and operational modeling tools. With the passage of the CALFED Bay-Delta Authorization Act (CBDAA), Reclamation, in partnership with DWR, initiated several joint studies to determine the feasibility of constructing additional storage in the Sacramento and San Joaquin basins. Although still under study, this coordination between Reclamation, DWR, and potential project beneficiaries has contributed significantly to improved understanding of potential opportunities and challenges for increasing the yield of the CVP and SWP systems while supporting basin ecosystem needs. Reclamation also has responded to CVPIA and CBDAA congressional mandates to work closely with DWR on addressing the challenges of California's future water needs. One of these challenges is climate change. In response, Reclamation and DWR have begun to coordinate closely on the development of common methods, shared data, and modeling tools along with coordinated stakeholder outreach activities between DWR's California Water Plan and Reclamation's Central Valley Integrated Resource Plan project activities. In the near future, additional coordination with DWR and other partners likely will be expanded to other climate-related activities including Reclamation's WaterSMART grants to develop climate analysis tools and through the WaterSMART Basin Study Program.

7.2 Historical Climate

The historic climate of the Central Valley is characterized by hot and dry summers and cool and damp winters. Summer daytime temperatures can reach 90 °F with occasional heat waves bringing temperatures exceeding 115 °F. The majority of precipitation occurs from mid-autumn to mid-spring. The Sacramento Valley receives greater precipitation than the San Joaquin and Tulare Lake basins. In winter, temperatures below freezing may occur, but snow in the valley lowlands is rare. The Central Valley typically has a frost-free growing season ranging from 225 to 300 days. During the growing season, relative humidity is characteristically low; in the winter, values are usually moderate to high, and ground fog may form. The Central Valley is located within the zone of prevailing westerly winds, but local terrain exerts a significant influence on wind directions. Warmer-than-normal temperatures often are associated with more northerly winds flowing out of the Great Basin to the east. During summer, strong westerly winds driven by the large temperature difference between the San Francisco Bay and interior Great Valley often occur in the Sacramento-San Joaquin Delta.

The inter-annual variability of the Central Valley climate is strongly influenced by conditions occurring in the Pacific Ocean including the El Nino Southern Oscillation (ENSO) and the existence of a semipermanent high-pressure area in the northern Pacific Ocean. During the summer season, the northerly position of the Pacific high blocks storm tracks well to the north and results in little summertime precipitation. During the winter months, the Pacific high typically moves southward allowing storms into the Central Valley. Such storms often bring widespread, moderate rainfall to the Central Valley lowlands and the accumulation of snow in the surrounding mountainous regions. When strong ENSO global circulation patterns occur, storm centers can approach the California coast from a southwesterly direction, transporting large amounts of tropical moisture with resulting heavy rains that can produce high runoff and the potential for widespread flooding in the Central Valley.

Over the course of the 20th century, warming has been prevalent over the Sacramento and San Joaquin River basins. Basin average mean-annual temperature has increased by approximately 2 °F during the course of the 20th century for just the Sacramento River basin above the Delta (figure 46) or the San Joaquin River basin above the Delta (figure 47).

Warming has not occurred steadily throughout the 20th century. Increase in temperature occurred primarily during the early part of the 20th century between 1910–1935. Subsequently, renewed warming began again in the mid-1970s and appears to be continuing at present, as shown for the Sacramento River basin

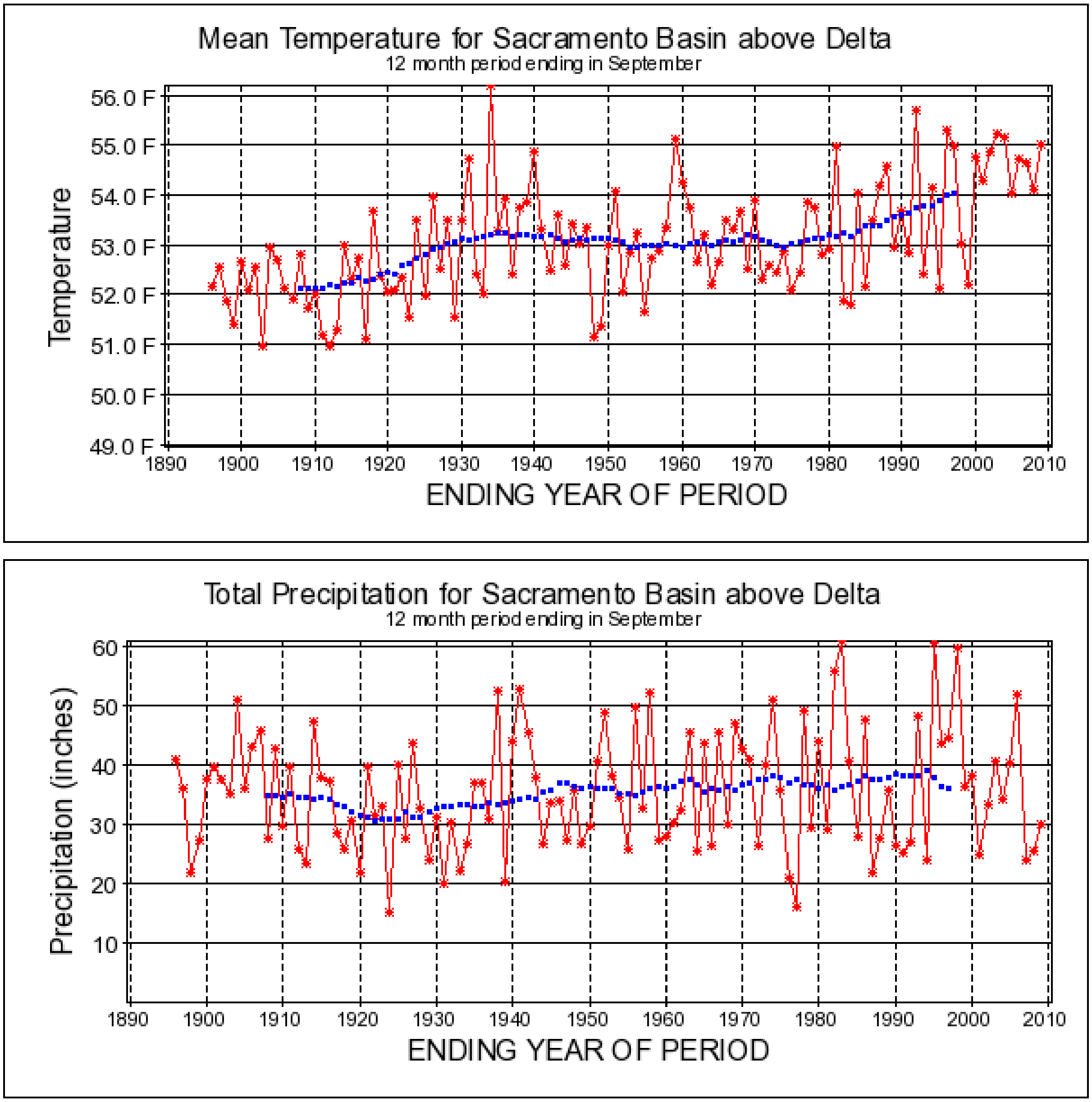
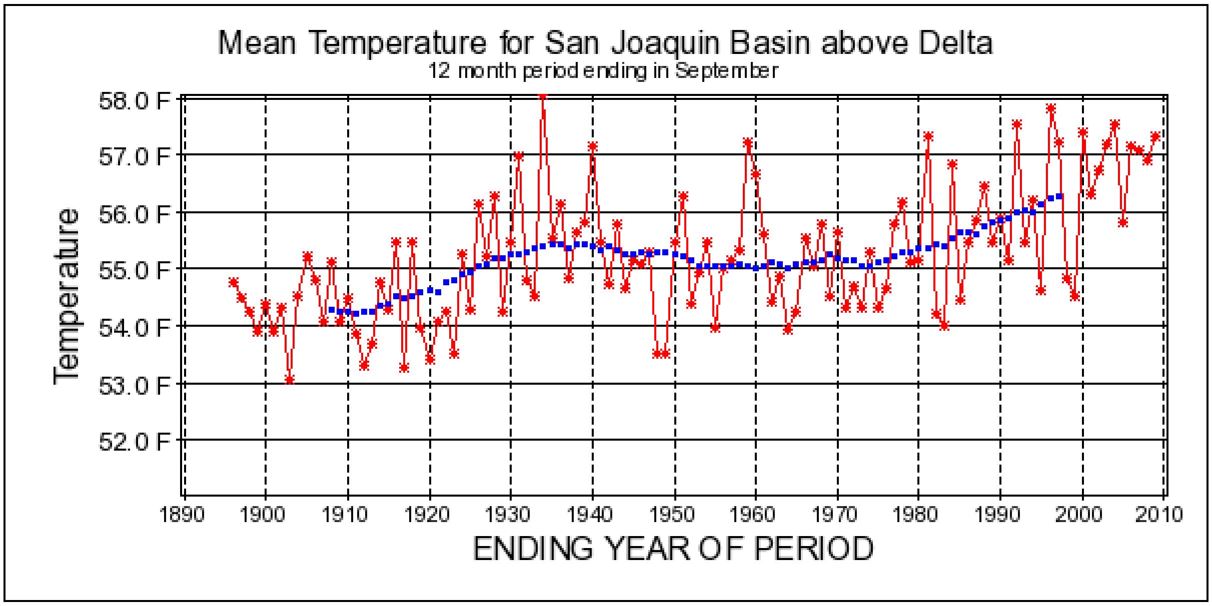


Figure 46. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Sacramento River basin.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).



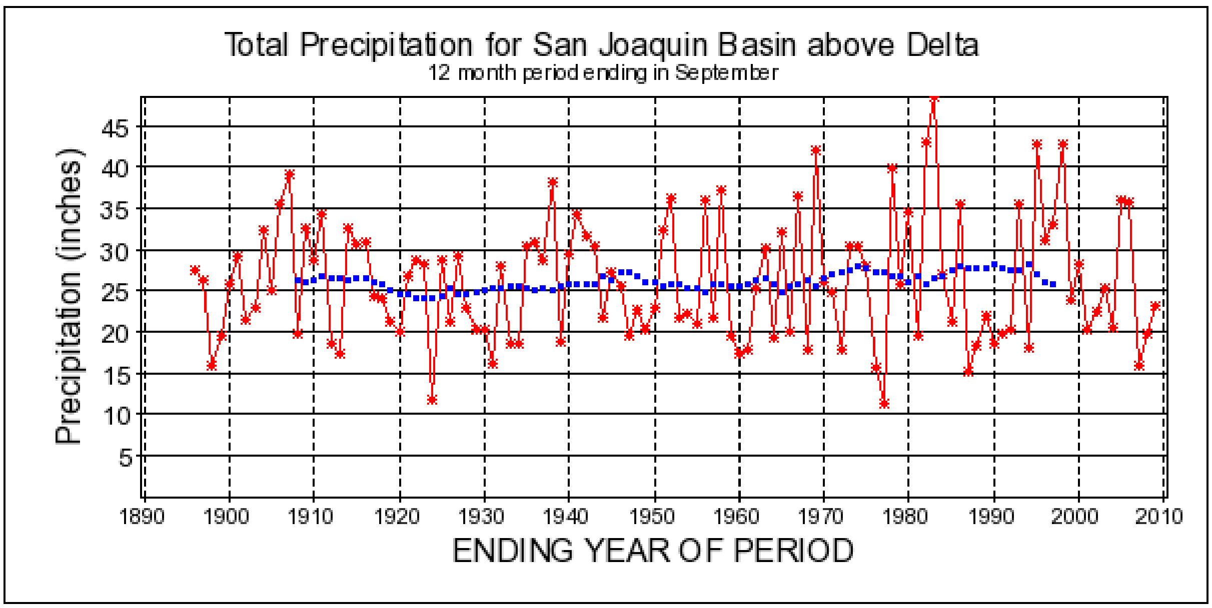


Figure 47. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the San Joaquin River basin.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

(figure 46 top panel). Similar results are apparent for the San Joaquin River basin (figure 47) and have been reported in other studies. Cayan et al. (2001) reported that Western United States spring temperatures have increased 1–3 ^{o}C (1.8–5.4 ^{o}F) since the 1970s; whereas, increased winter temperature trends in central California were observed to average about 0.5 °C (0.9 °F) per decade (Dettinger and Cayan 1995). In both the Sacramento and San Joaquin basins, the overall 20th century warming has been about 3 °F.

In the Sacramento basin, the warming trend also has been accompanied by a gradual trend starting in the 1930s toward increasing precipitation (figure 46, bottom panel). However, a similar precipitation trend is not evident in the San Joaquin basin (figure 47). Other studies have shown similar results. Regonda et al. (2005) reported increased winter precipitation trends during 1950–1999 at many Western United States locations, including several in California's Sierra Nevada; but a consistent regionwide trend was not apparent. Interestingly, the variability of annual precipitation, as can be seen by comparing the range of differences in high and low values of the solid red line, appears to have increased in the latter part of the 20th century. These extremes in wet and dry years have been especially frequent since the mid-1970s in both the Sacramento and San Joaquin basins.

7.3 Historical Hydrology

Streamflow in the Sacramento River and San Joaquin River basins has historically varied considerably from year to year. Runoff also varies geographically; during any particular year, some portions of the basin may experience relatively greater runoff conditions while others areas experience relatively lesser runoff (e.g., more abundance runoff in the northern Sacramento Valley versus relatively drier conditions in southern San Joaquin Valley). On a monthly to seasonal basis, runoff is generally greater during the winter to early summer months, with winter runoff generally originating from rainfall-runoff events and spring to early summer runoff generally supported by snowmelt from the Cascade Mountains and Sierra Nevada.

The historic changes in climate described in preceding sections have resulted in several important effects on Sacramento and San Joaquin basin hydrology. Although annual precipitation may have slightly increased or remained relatively unchanged, corresponding increases in mean annual runoff in the Sacramento and San Joaquin Rivers did not occur (Dettinger and Cayan 1995). One observed change is in the seasonal timing of runoff. In the Sacramento River basin, a decrease of about 10% in fraction of total runoff occurring between April–July has been observed over the course of the 20th century (Roos 1991). Similar results were obtained from analyses of the combined basin runoffs for both the Sacramento and San Joaquin basins by Dettinger and Cayan (1995). Along with the declining spring runoff, corresponding increases in the winter runoff have been observed. Analysis of data for 18 Sierra Nevada river basins found earlier runoff trends (Peterson et al. 2008). Of the potential climatic factors that could produce such changes, analyses indicated that increasing spring temperatures rather than increased winter precipitation was the primary cause of the observed trends (Cayan 2001). Studies by these researchers and others showed that the magnitude of the decreases in April–July runoff was correlated with the altitude of the basin watershed. High altitude basins like the San Joaquin exhibited less decrease in spring runoff than lower elevation watersheds such as the Sacramento. However, it is noted that the appearance of runoff trends in the basins depends on location and period of record being assessed. For example, runoff trends were evaluated for this report during the last half of the 20th century; and although similar trend directions were founds, they were found to be statistically weak.[9]

Other studies of the magnitude of spring snowpack changes during the 20th century found that snowpack as measured by April 1st SWE showed a decreasing trend in the latter half of the 20th century (Mote 2006). Coincident with these trends, reduced snowpack and snowfall ratios were indicated by analyses of 1948–2001 SWE measurements at 173 Western United States stations (Knowles et al. 2007). Regonda et al. (2005) reported decreasing spring SWE trends in 50% of Western United States locations evaluated.

The changes discussed in the previous paragraphs over regional drainages such as the Sacramento and San Joaquin River basins are sensitive to the uncertainties of station measurements as well as the period of analysis and analyzed location. For the entire Western United States, observed trends of temperature, precipitation, snowpack, and streamflow might be partially explained by anthropogenic influences on climate (e.g., Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009). However, it remains difficult to attribute observed changes in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends in precipitation (Hoerling et al. 2010) and for trends in basin-scale conditions rather than at the larger Western United States scale (Hidalgo et al. 2009). Sea level

[9] Trend significance was assessed using statistical testing during the period of 1951–1999 applied to historical simulated runoff results under observed historical weather conditions (Reclamation 2011a). Trends were computed and assessed for four Missouri basin locations, focusing on annual and April–July runoff. In all cases, computed trends were judged to not be statistically significant with 95% confidence.

change is also an important factor in assessing the effect of climate on California's water resources because of its effect on water quality in the Sacramento-San Joaquin Delta. Higher msl is associated with increasing salinity in the Delta, which influences the suitability of its water for agricultural, urban, and environmental uses. The global rate of msl change was estimated by IPCC (2007) to be 1.8 +/- 0.5 mm/yr (0.07 +/- 0.02 in/yr) from 1961–2003 and 3.1 +/- 0.7 mm/yr (0.12 +/ 0.03 in/yr) during 1993–2003. During the 20th century, msl at Golden Gate Bridge in San Francisco Bay has risen by an average of 2 mm/yr (0.08 in/yr) (Anderson et al. 2008b). These rates of sea level rise appear to be accelerating based on tidal gauges and remote sensing measurements (Church and White 2006; Beckley et al. 2007).

7.4 Future Changes in Climate and Hydrology

This section summarizes results from studies focused on future climate and hydrologic conditions within the Sacramento and San Joaquin River basins. Section 7.4.1 focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document.

7.4.1 Projections of Future Climate

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the perspective of basin-average and, secondly, as those climate conditions are distributed throughout the basin. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented; and, finally, climate and snowpack changes translated into effects on annual and seasonal runoff as well as acute runoff events relevant to flood control and ecosystems management are discussed.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Sacramento and San Joaquin basins may increase steadily during the 21st century. Focusing on the Sacramento River subbasin at Freeport, San Joaquin River subbasin at Vernalis, and on the combined basins inflow to the Delta (figure 48), the basin-average mean-annual temperature is projected to increase by roughly 5–6 °F during the 21st century. For each subbasin view, the range of annual possibility appears to widen through time.

The ensemble mean of projections indicates that mean-annual precipitation, averaged over either subbasin (figure 48), appears to stay generally steady during the 21st century, with perhaps a slight increase in the northern portion of the Central Valley (Sacramento River subbasin at Freeport) and a slight decrease within the southern portion (San Joaquin River subbasin at Vernalis). This is evident by following the ensemble median of the annual precipitation through time for both basins. The projections also suggest that annual precipitation in the Sacramento and San Joaquin basins should remain quite variable over the next century. Despite the statements about the mean of the ensemble, there is significant disagreement among the climate projections regarding change in annual precipitation over the region.

Projection of climate change is geographically complex over the Sacramento and San Joaquin River basins, particularly for precipitation. For example, consider the four decades highlighted on figure 48 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, in the Sacramento River subbasin at Freeport (figure 49, top left panel), annual average temperatures are generally cooler in the high-elevation upper reaches in the north and along the mountainous rim to the east. Warmer temperatures occur to the south and in the lower lying valley area. This is similarly the case for the San Joaquin River subbasin at Vernalis (figure 50, top left panel). For precipitation, amounts are generally greater along the mountainous spine extending from the Cascades in the north-central part of the basin throughout the Sierra Nevada to the southeast (figure 51, top left panel) and lesser in the interior plateau northeast of these mountain ranges and in the lower lying valley areas to the south and west. In the San Joaquin, precipitation amounts are also greater in the Sierra Nevada (figure 52, top left panel).

Regarding climate change, temperature changes are generally uniform over both the Sacramento River (figure 49) and San Joaquin River subbasins (figure 50) and steadily increase through time. Changes are projected to be perhaps slightly greater in the eastern portions of the basins. For precipitation, similar geographic

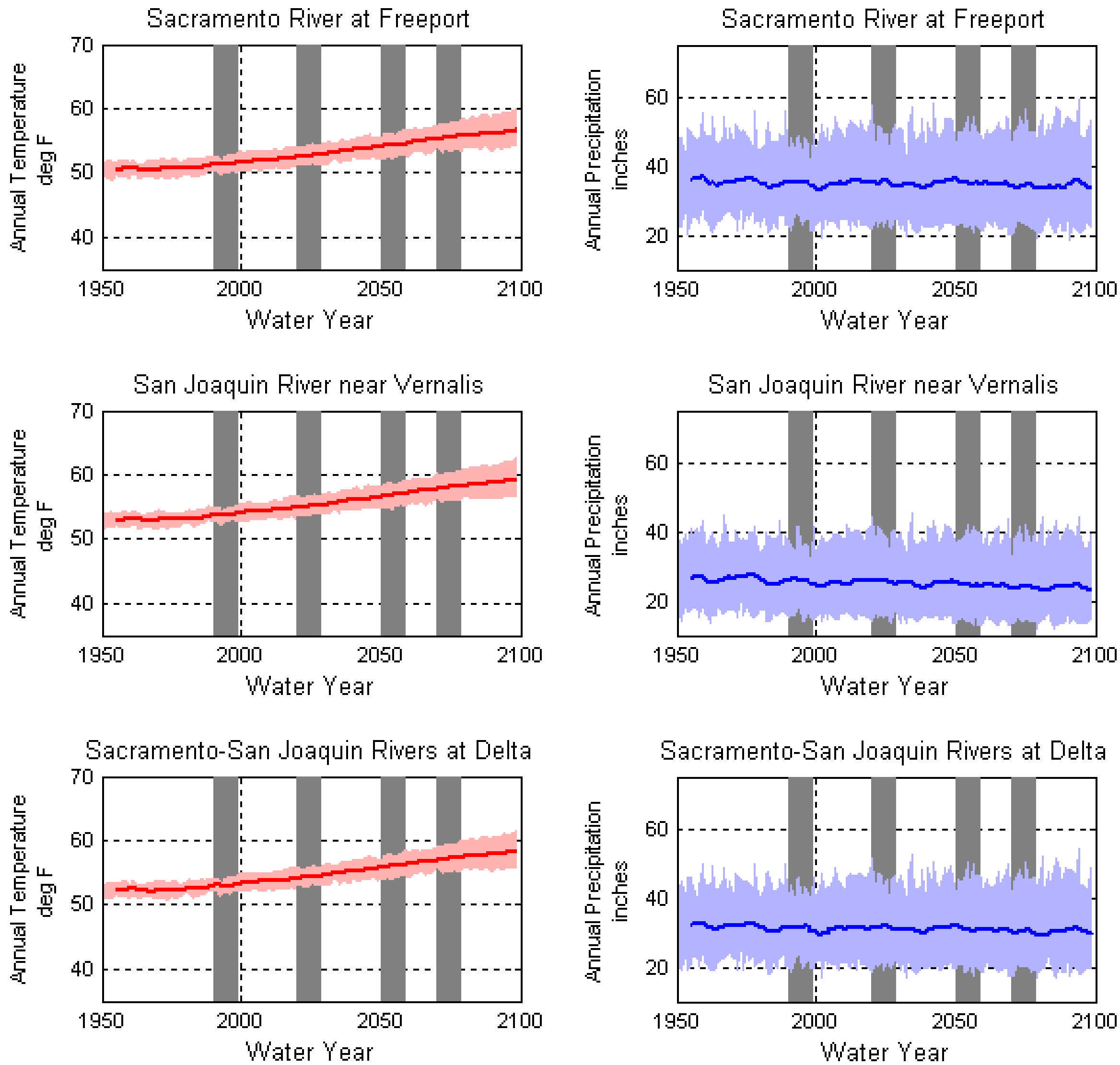


Figure 48. Simulated annual climate averaged over Sacramento and San Joaquin River subbasins.

Figure 48 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10^{th} to 90^{th} percentile annual values within the ensemble from simulated 1950 through simulated 2099.

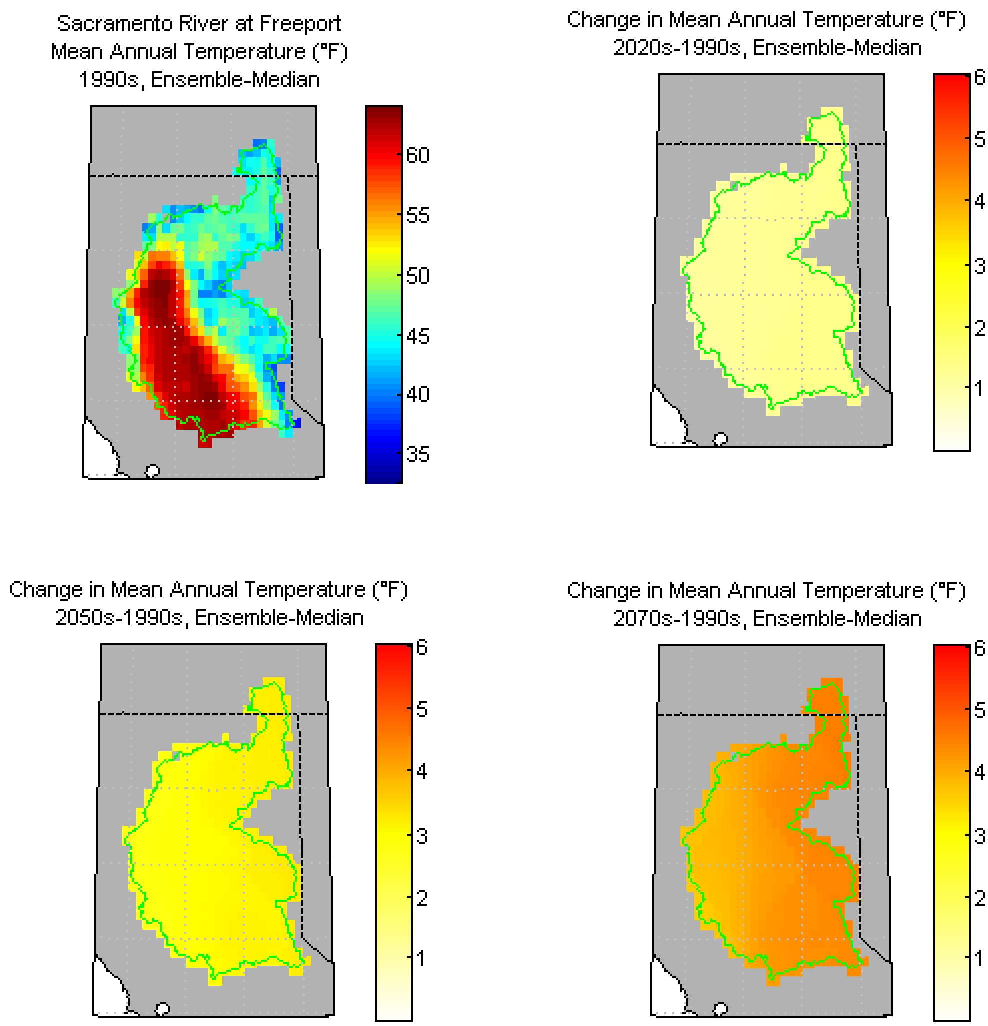


Figure 49. Simulated decade-mean temperature over the Sacramento River basin above Freeport, California.

Figure 49 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

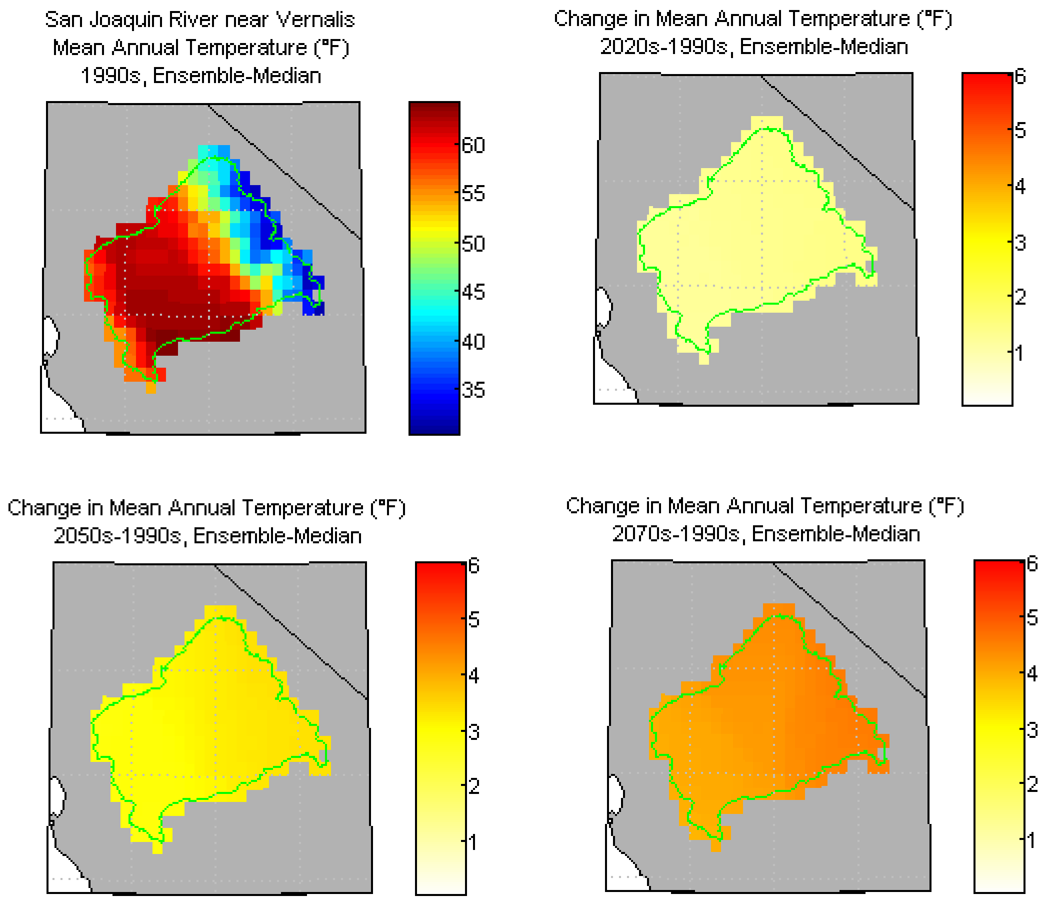


Figure 50. Simulated decade-mean temperature over the San Joaquin River basin above Vernalis, California.

Figure 50 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

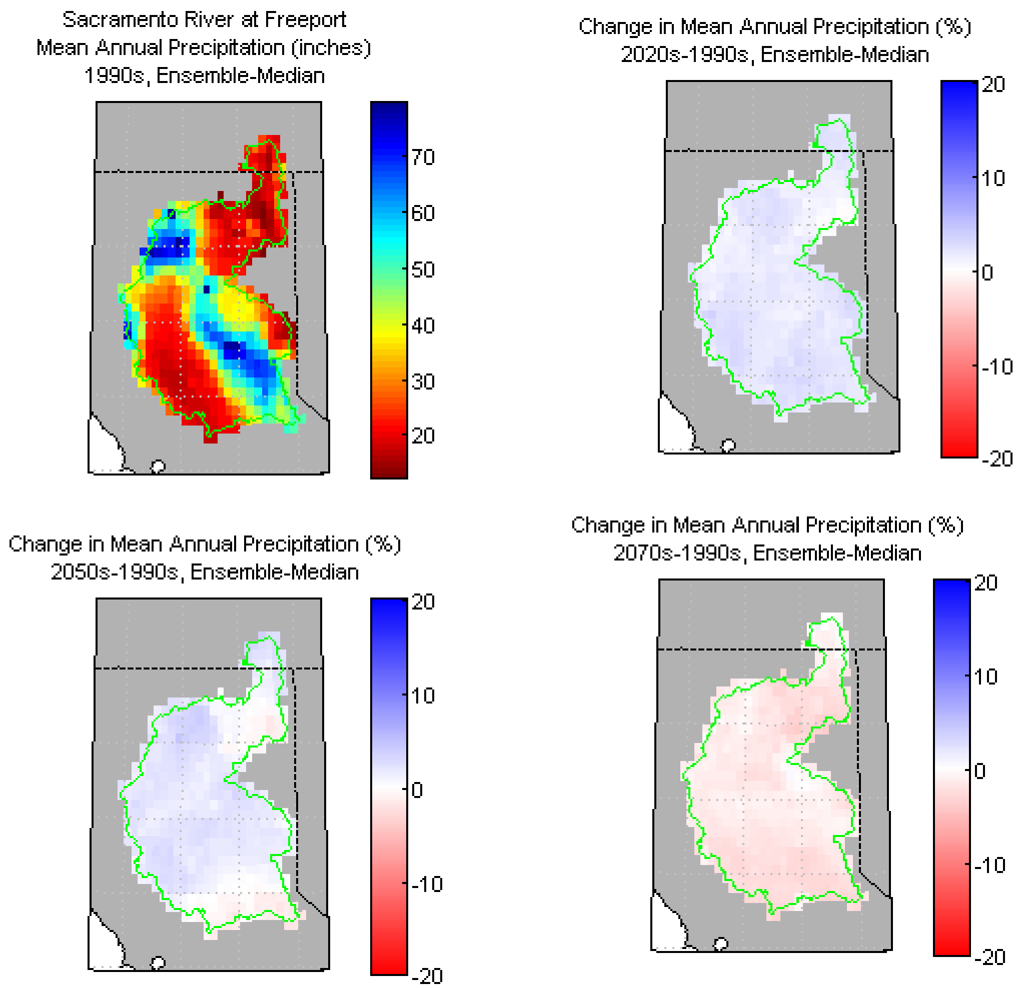


Figure 51. Simulated decade-mean temperature over the Sacramento River basin above Freeport, California.

Figure 51 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

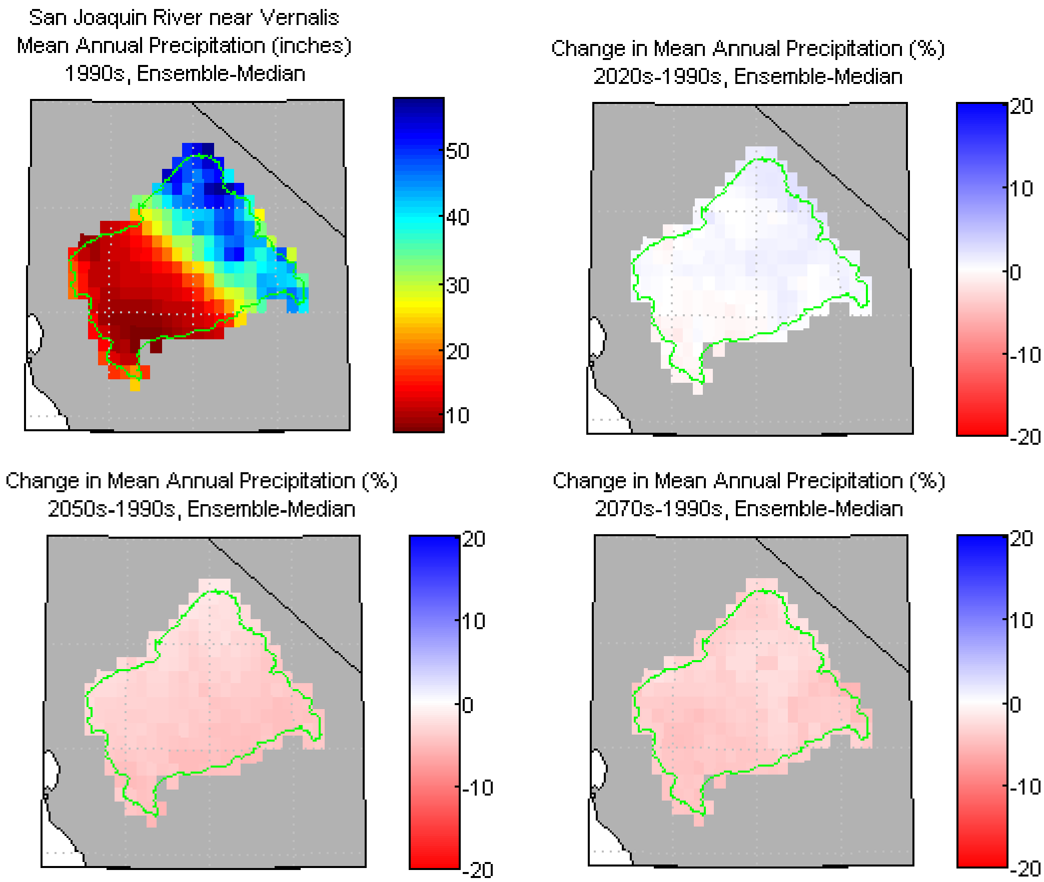


Figure 52. Simulated decade-mean temperature over the San Joaquin River basin above Vernalis, California.

Figure 52 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

consistency is found, although there is a little less uniformity in the direction of change between the two basins and through the progression of 21st century decades. For example, the Sacramento River basin is projected to generally experience a slight increase in precipitation during the early to mid 21st century (2020s and 2050s) followed by a reversal to a slight precipitation decline (2070s). In the San Joaquin River basin, a similar progression is projected but with the reversal occurring earlier in the 21st century (i.e., slight increase to no change in preciptation projected for the 2020s followed by slight decrease by the 2050s and continuing through the 2070s). It it important to note that, while the mean-annual amount of precipitation may only change slightly under increasing temperature projections, the character of precipitation within the Sacramento and San Joaquin River basins also is expected to change under warming conditions, resulting in more frequent rainfall events, less frequent snowfall events.

Temperature and precipitation changes are expected to affect hydrology in various ways including snowpack development. As noted previously, increased warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify changes in snowpack, it is apparent that the projected warming in the Sacramento River and San Joaquin River basins tends to dominate projected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figures 53 and 54 for the two basins, respectively). Snowpack decrease is projected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. Such areas include much of the northern Sierra Nevada and Cascade Mountains of the Sacramento River basin as well as lower to middle elevations in the southern Sierra Nevada of the San Joaquin River basin. However, even in the highest elevations of the southern Sierra Nevada, losses are projected to be significant by the late 21st century.

Changes in climate and snowpack within the Sacramento and San Joaquin River basins will change the availability of natural water supplies. These effects may be experienced in terms of changes to annual runoff and changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) offset or amplify the effect. Results from Reclamation (2011a) suggest that annual runoff effects are generally consistent but do slightly vary by location within the basins (figure 55), depending on baseline climate and the projected temperature and precipitation changes. For example, in the Sacramento River and its major

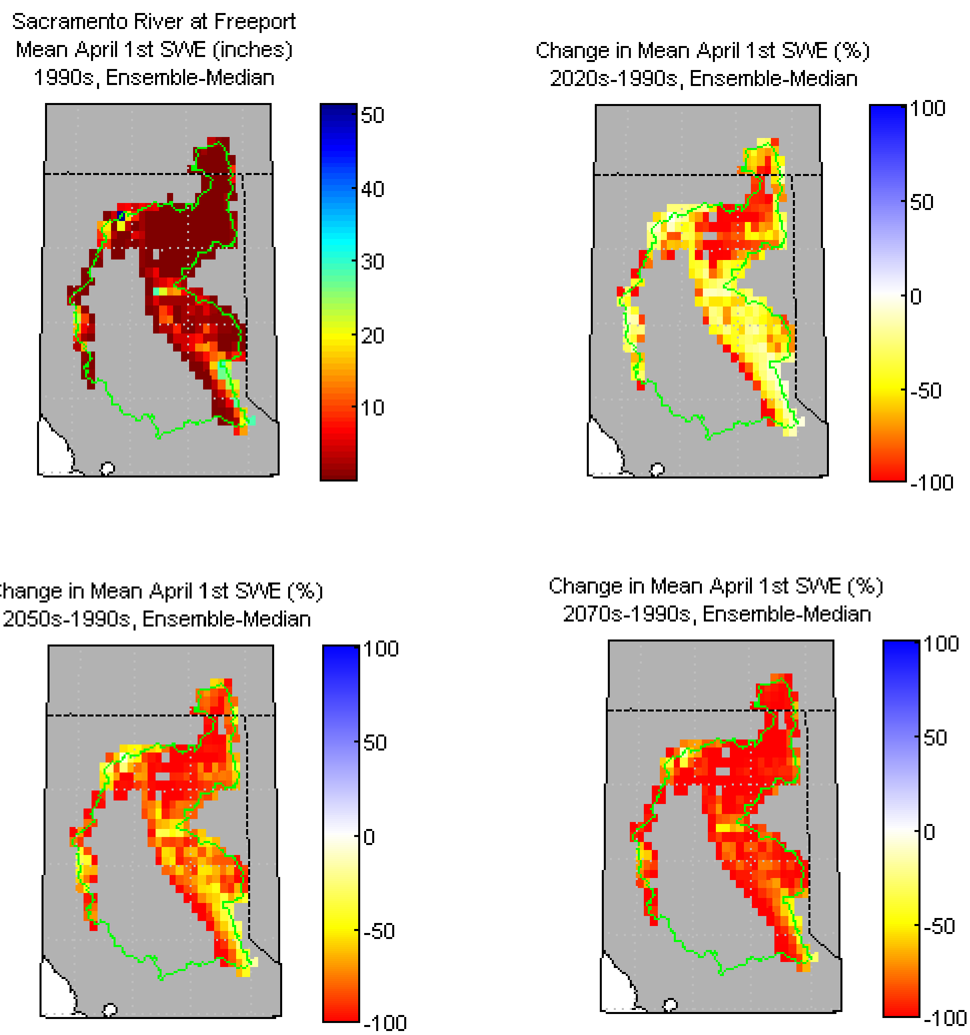


Figure 53. Simulated decade-mean April 1st snowpack over the Sacramento River basin above Freeport, California.

Figure 53 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

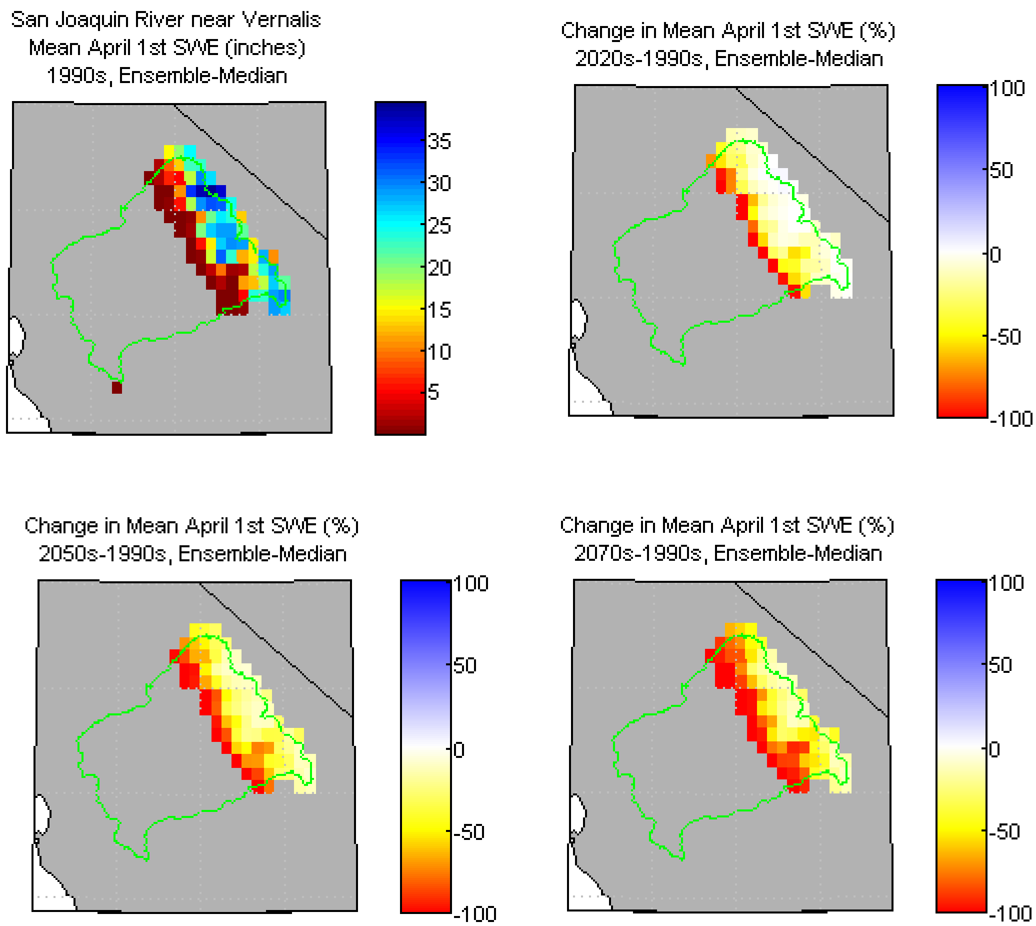


Figure 54. Simulated decade-mean April 1st snowpack over the San Joaquin River basin above Vernalis, California.

Figure 54 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

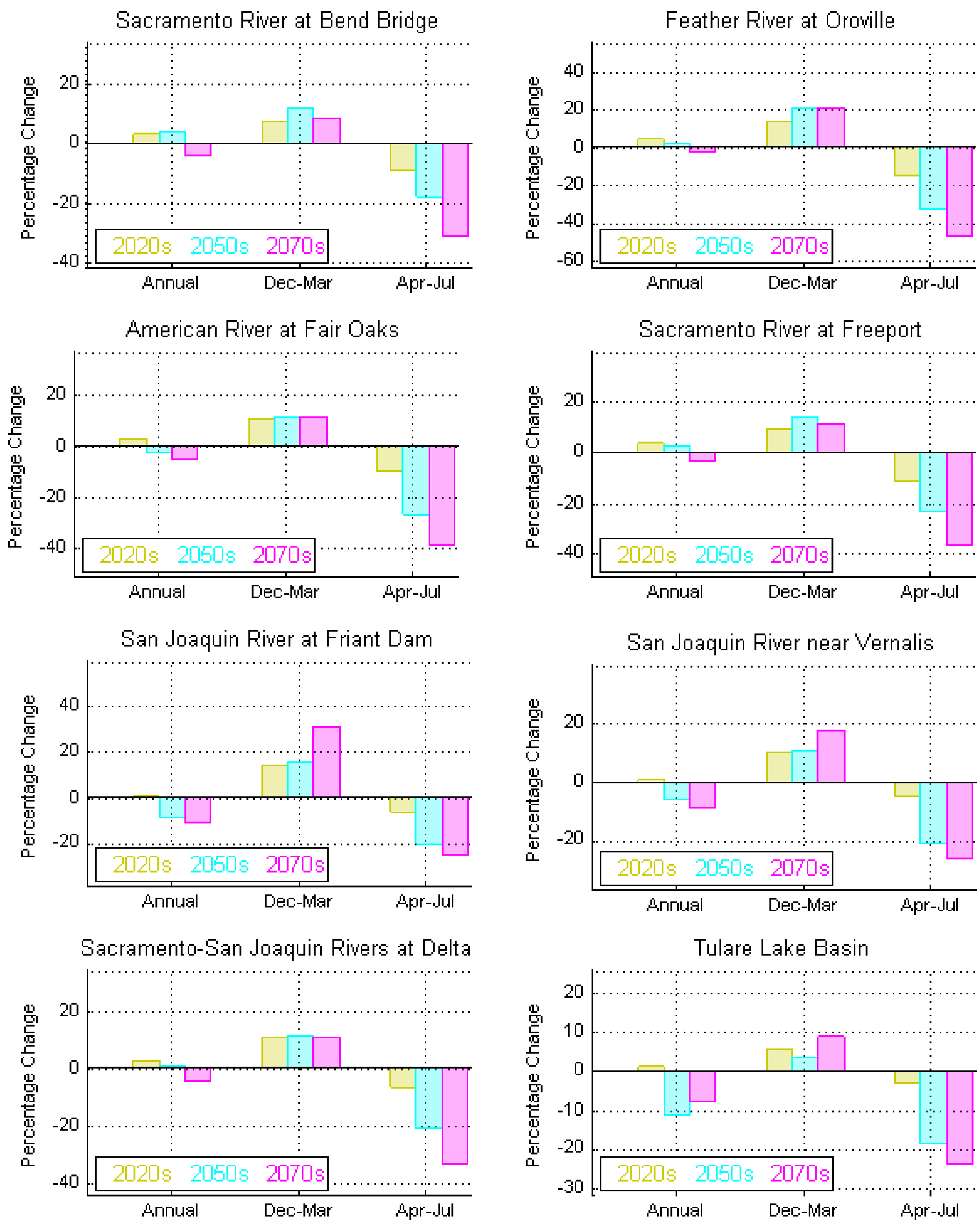


Figure 55. Simulated changes in decade-mean runoff for several subbasins in the Sacramento and San Joaquin River basins.

Figure 55 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

tributaries, the Feather River and the American River, annual runoff increases very slightly during the early and middle part of the 21st century. However, in all of these watersheds, a slight decline is projected to occur in the latter half of the century. In the San Joaquin River basin and its major tributaries, similar results are found but with mean-annual runoff declines projected to occur by the mid-21st century.

The seasonality of runoff is also projected to change. Warming may lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This conceptually leads to increases in December–March runoff and decreases in April–July runoff. Results over the two subbasins suggest that this concept generally holds throughout the two basins, but the degree of seasonal change does vary by subbasin location (figure 54). This combination of increased winter and decreased spring runoff points to the important role of temperature in determining 21st century seasonal water supplies for both basins. In the lower right-hand corner of figure 54, the combined runoff change is depicted based on runoff changes in the Sacramento River, San Joaquin River, and other Delta tributaries. Overall, the changes are more similar to those found in the Sacramento River basin and are reflective of the larger contribution of the Sacramento River (see Sacramento River at Freeport) relative to the San Joaquin River (see San Joaquin at Vernalis) to Delta flows. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to acute runoff events are also of interest as they relate to flood control and ecosystem management in both basins. There is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. For this discussion, annual maximum- and minimum-week runoff are used as metrics of acute runoff events (figure 56). The maximum weekly runoff typically occurs sometime between late fall and early summer, whereas the minimum weekly runoffs are most likely to occur between late summer and early fall. Because the selected locations are upstream of major aquifers in the Central Valley, the runoff extremes are affected only minimally by ground water and bank storage processes.

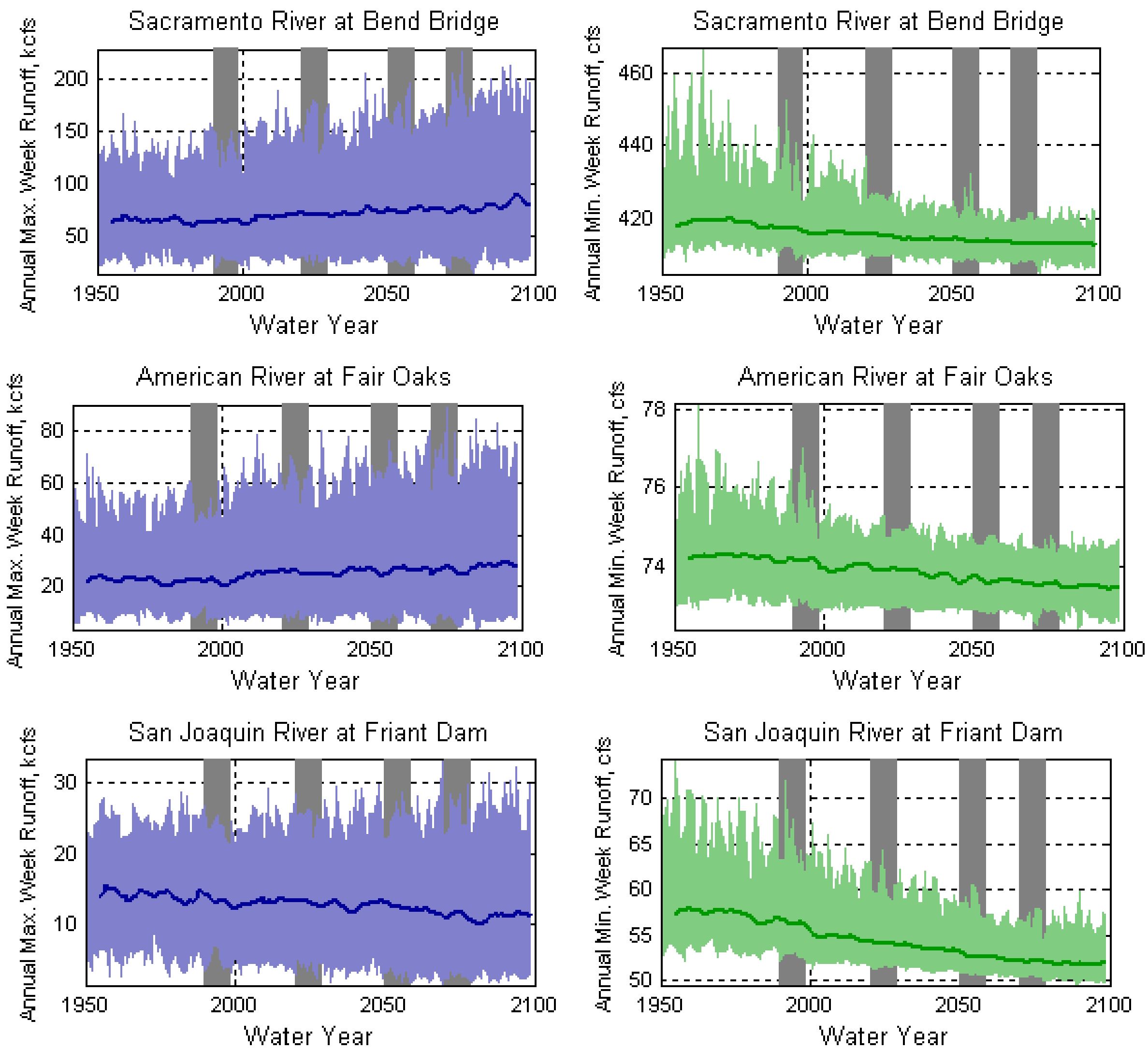


Figure 56. Simulated annual maximum and minimum week runoff for several subbasins in the Sacramento and San Joaquin River basins.

Figure 56 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step, but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

For annual maximum-week runoff, results for the Sacramento River and San Joaquin River basins appear to differ. For the two subbasins shown in the Sacramento River basin, it appears that expected annual maximum-week runoff may gradually increase during the 21st century. The range of possibility also appears to increase during the century. These findings raise questions about whether increase in maximum weekly runoff may be indicative of potentially greater flood risks during the 21st century. However, for the San Joaquin River subbasin at Friant Dam, results suggest a slight decline in annual maximum-week runoff.

For annual minimum-week runoff, results suggest a gradual decrease in the expected annual value as the 21st century progresses. The range of projected possibility also reduces with time. These declines are likely the result of decreased snowpack accumulation and increased soil evaporation and plant transpiration in the upper watershed. Decreasing minimum runoff may lead to adverse affects on aquatic habitats by both reducing wetted stream perimeters and availability of aquatic habitat and through increased water temperatures detrimental to temperature-sensitive aquatic organisms.

A summary of climate and hydrologic changes is provided in table 6 for four subbasins of the Sacramento River and San Joaquin River basins: Sacramento River at Bend Bridge, Sacramento River at Freeport, San Joaquin River at Friant Dam, and San Joaquin River at Vernalis. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

7.4.2 Other Studies of Future Climate and Hydrology

Future changes in Central Valley climate and hydrology have been the subject of numerous studies. A good summary of studies completed prior to 2006 was published by Vicuna and Dracup (2007). For the Central Valley watersheds, Moser et al (2009) reports specifically on future climate possibilities over California and suggest that warmer temperatures are expected during the 21st century, with an end-of-century increase of 3–10.5 °F. For mean annual precipitation in northern California, the study indicates a generally decreasing trend of between 10 to 15% by the end of the century.

The effects of projected changes in future climate were assessed by Maurer (2007) for four river basins in the western Sierra Nevada contributing to runoff in the Central Valley. These results indicate a tendency toward increased winter precipitation; this was quite variable among the models, while temperature increases and associated SWE projections were more consistent. The effect of

Table 6. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Sacramento and San Joaquin River basins

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Sacramento River at Bend Bridge			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1st Snow Water Equivalent (%)	-53.4	-75.9	-88.6
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
Sacramento River at Freeport			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1st Snow Water Equivalent (%)	-53.4	-75.9	-88.6
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
San Joaquin River at Friant Dam			
Mean Annual Temperature (°F)	1.4	3.3	4.5
Mean Annual Precipitation (%)	-1.3	-5.3	-8.6
Mean April 1st Snow Water Equivalent (%)	-23.1	-39.6	-48.7
Mean Annual Runoff (%)	0.7	-8.7	-10.7
Mean December–March Runoff (%)	13.9	15.8	31.0
Mean April–July Runoff (%)	-6.1	-20.2	-25.0
Mean Annual Maximum Week Runoff (%)	-2.3	-6.6	-16.0
Mean Annual Minimum Week Runoff (%)	-4.0	-6.4	-7.6
San Joaquin River at Vernalis			
Mean Annual Temperature (°F)	1.3	3.1	4.3
Mean Annual Precipitation (%)	-1.0	-4.2	-7.7
Mean April 1st Snow Water Equivalent (%)	-27.2	-45.9	-56.3
Mean Annual Runoff (%)	0.8	-5.9	-8.4
Mean December–March Runoff (%)	10.1	10.7	17.2
Mean April–July Runoff (%)	-4.8	-20.6	-25.8
Mean Annual Maximum Week Runoff (%)	1.6	-1.8	-4.9
Mean Annual Minimum Week Runoff (%)	-1.2	-1.9	-2.3

increased temperature was shown by Kapnick and Hall (2009) to result in a shift in the date of peak of snowpack accumulation to 4–14 days earlier in the winter season by the end of the century. Null et al. (2010) reported on climate change impacts for 15 western-slope watersheds in the Sierra Nevada under warming scenarios of 2, 4, and 6 °C increase in mean-annual air temperature relative to historical conditions. Under these scenarios, total runoff decreased; earlier runoff was projected in all watersheds relative to increasing temperature scenarios; and decreased runoff was most severe in the northern part of the Central Valley. This study also indicated that the high elevation southern-central region was more susceptible to earlier runoff, and the central region was more vulnerable to longer low flow periods.

Sea level changes also have been projected to occur during the 21st century due to increasing air temperatures causing thermal expansion of the oceans and additional melting of the land-based Greenland and Antarctic ice sheets (IPCC 2007). The CALFED Independent Science Board estimated a range of sea level rise at Golden Gate of 1.6–4.6 feet by the end of the century (CALFED ISB 2007). The California Department of Water Resources used the 12 future climate projections to estimate future sea levels. Their estimates indicate sea level rise by mid-century ranges from 0.8–1.0 feet with an uncertainty range spanning 0.5–1.3 feet. By the end of the century, sea level rise projections ranged from 1.8–3.1 feet, with an uncertainty range spanning from 1.0–3.9 feet. There is also the potential for increased extremely high sea level events to occur when high tides coincide with winter storms (Moser et al. 2009).

7.5 Future Implications for Water and Environmental Resources

7.5.1 Water Supply, Reservoir Operations and Flood Management

Warming without precipitation change over the Sacramento and San Joaquin River basins likely would lead to increased watershed evapotranspiration, decrease spring snowpack and snowmelt, and, ultimately, reduced manageable water supplies (Moser et al. 2009). Current climate projections suggest that precipitation should progress from initially steady or slightly increasing to eventually a slight decrease over much of the region. Such a decrease would amplify warming only effects. Other potential warming impacts could affect supplies, including increased reservoir and stream evaporation, and runoff effects from watershed vegetation changes (e.g., change in forest cover or vegetation transitions).

Based on current reservoir operations constraints (e.g., capacity, flood control rules), shifts in seasonal runoff likely would lead to reduced water supplies. This expectation is based on current operating conditions that limit storage opportunities during winter runoff season at numerous basin reservoirs and that increased winter runoff would not necessarily translate into increased storage of water leading into the spring season. Conversely, storage capture of snowmelt runoff has traditionally occurred during the late spring and early summer seasons. Reductions in runoff during this season likely would translate into reductions in storage capture and, likewise, reductions in water supply for warm season delivery.

An additional challenge facing Central Valley water managers is how to balance year-to-year management of drought risk with maximizing reservoir releases to satisfy instream and delivery objectives during any given year. Typically, major reservoirs are operated to retain a certain amount of water in storage at the end of the summer season. This carryover storage is essentially a savings account to be used in the event of a future drought condition. With warming temperatures resulting in the need to release a greater fraction of runoff to maintain flood protection and greater amounts of reservoir evaporation during warm months, it is likely that the ability to meet carryover storage targets will be increasingly challenged. Another important operational concern is that CVP reservoirs are operated to release cold water during the late summer and early fall months to provide suitable habitat conditions for anadromous fish survival. With climate warming, the quantity of suitable cold water in storage is likely to decrease even as the need for this water, due to higher river water temperatures, is likely to increase. Potential adjustments to current operational practices to these issues have been studied by a number of investigators including Van Rheenan et al. (2004), Anderson et al. (2008), Brekke et al. (2009), and Moser et al. (2009).

Addressing flood control, the projected increase in winter runoff volumes raises additional uncertainties about the depth of reservoir drafting required to sustain flood protection levels into the 21st century. One of the primary benefits provided by CVP reservoirs is protection against flood damages by maintaining relatively low levels of reservoir storage during the winter months. However, as described in the preceding section, hydrologic changes during the 21st century are projected to include both proportionately more winter runoff and more extreme runoff events. These conditions could create increased challenges to maintain adequate flood protection. More analysis is required to identify the spectrum of seasonal-to-acute runoff events relevant to current flood control operations, how these runoff events may change during the 21st century, and how current operating procedures may or may not be challenged in managing such future events. A framework for estimating flood frequency in the context of climate projection information was applied (Raff et al. 2009) to several basins in the Western United States including the San Joaquin. Their results showed that, under current climate projections, annual maximum flows would tend to increase.

7.5.2 Hydropower

Electricity demand, from hydropower generation and other sources, generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

7.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat. For example, Wagner et al. (2011) show that changes in water temperatures caused by climate change in California’s Sacramento-San Joaquin Delta will affect the ecosystem through physiological rates of fishes and invertebrates, and that the Delta smelt (analyzed as a “key species”) would experience an increase in the number of days above temperatures causing high mortality (especially along the Sacramento River) and a shift in thermal conditions for spawning to earlier in the year. Warmer air and water temperatures potentially could improve habitat for quagga mussels and other invasive species that, in turn may additionally impact maintenance of hydraulic structures and increased risk of watershed vegetation disturbances due to increased fire potential. Climate changes could decrease the effectiveness of chemical or biological agents used to control invasive species (Hellman et al. 2008). Warmer water temperatures also could spur the growth of algae, which could result in eutrophic conditions in lakes, declines in water quality (Lettenmaier et al. 2008), and changes in species composition. Other warming-related impacts include poleward shifts in the geographic range of various species, impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change also can trigger synergistic effects in ecosystems and exacerbate invasive species problems.

Luce and Holden (2009) discuss the potential for fish and wildlife impacts if observed streamflow reduction trends continue into the future. For the Central Valley, increasing temperatures are likely to increase challenges for providing suitable habitat conditions for salmonid populations. In addition to warmer stream and estuary temperatures, increased winter flows and reduced summer and fall flows also will contribute to stress these species. Further, changes in seasonal runoff patterns may affect both adult and juvenile migration. Climate changes may trigger other affects associated with the ocean and estuary conditions after emigration because such conditions may not match the season-dependent conditions that these species have evolved to exploit. Climate-induced changes in flow and water quality in the Sacramento-San Joaquin Delta also may have significant effects on other native and exotic aquatic species.

7.5.4 Surface Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

7.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge; but this area needs further study.

In the Central Valley, ground water is an important source of water supply. Frequently, ground water aquifers are heavily used when surface water supplies are limited. Currently, about half of California's water supply for human consumption or use comes from ground water (Franco 2005). Consequently, climate-related decreases in surface water supplies and/or increases in demands are likely to pose significant challenges to future ground water management. The effects of climate change on the recharge of Central Valley aquifers will be important in determining the potential to capture high fall–winter runoff and store it for later use during periods of surface water shortage.

7.5.6 Water Demands

Potential climate changes to agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures; increased atmospheric carbon dioxide levels; and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Furthermore, these natural system changes must be considered in combination with socioeconomic changes including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Central Valley agriculture is one of California's major economic sectors, and the CVP is the major supplier of water to Central Valley farmers. Climate change poses potential challenges to both agricultural water supplies and demands. The effects of warming temperatures on water supplies have been described in previous sections, but changes in temperature along with changes in other atmospheric conditions including carbon dioxide have the potential to either increase or decrease irrigation water needs. For example, a literature review by Baldocci and Wong (2006) includes studies suggesting that elevated carbon dioxide gives crops a spurt in growth as photosynthesis responds positively to extra carbon dioxide. However, this positive response is not sustained because photosynthesis eventually experiences downward regulation. Elevated carbon dioxide also causes stomata to close (Baldocci and Wong 2006). This effect leads to water savings by reducing transpiration at the leaf scale. However, at the field scale, larger crops growing in a warmer climate will use more water. Baldocci and Wong (2006) also report that indirect effects of elevated carbon dioxide and warming on agriculture will include a lengthening of the growing and transpiration seasons, stimulation of weeds, and more insect pests; pollination also would be negatively impacted if warming causes a synchronization between flowering and the life cycle of insect pollinators.

Like the agricultural and environmental water demands discussed previously, climate change will have significant impacts on municipal, industrial, recreational, and environmental water demands. Outdoor urban water demands will respond to changes in atmospheric conditions in ways similar to agricultural crops. Indoor urban, industrial, and recreational demands strongly impact major socioeconomic factors such as population and economic growth conditions. In addition, land use planning, water pricing, and other regulatory considerations can have significant impacts on these demands.

8. Basin Report: Truckee

8.1 Basin Setting

The Truckee River basin in northeastern California and northwestern Nevada is a hydrographically closed basin and includes the Lake Tahoe watershed and headwater tributaries along the eastern slope of the Sierra Nevada. The Truckee River begins at the outlet of Lake Tahoe, generally flows north and east, through Reno and Sparks, and terminates in Pyramid Lake in the western Great Basin of Nevada (figure 57). The river is approximately 105 miles long with a watershed of 3,060 square miles. It is the primary source of municipal and industrial water for Reno and Sparks. River rafting and fly fishing are important recreational uses of the river, including a whitewater park on the river.

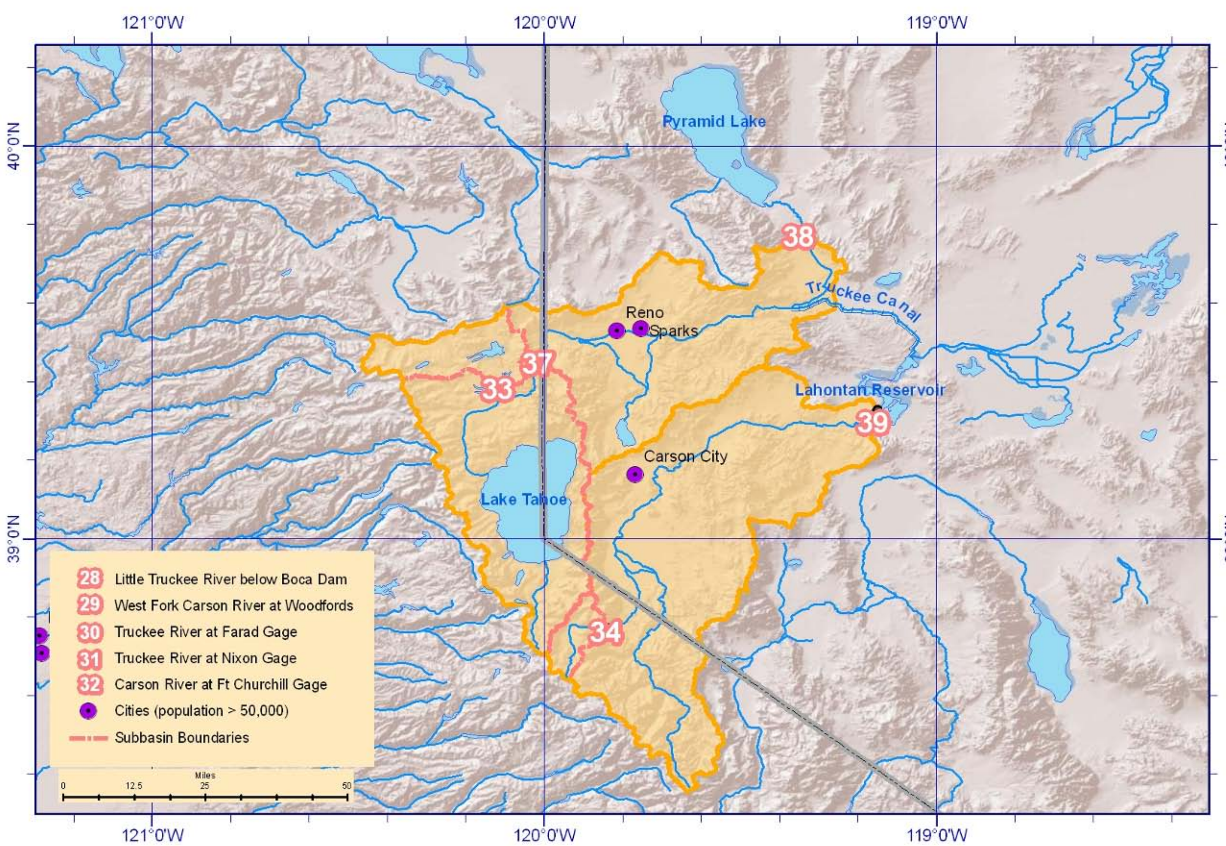


Figure 57. Truckee River basin, Carson River basins, and runoff-reporting locations for this report.

Reclamation coordinates with many entities in operations in the Truckee River basin including other Federal agencies, States, tribes, and local groups. A number of court decrees, agreements, and regulations govern day-to-day operations of

Truckee River with operations of the river being a joint multiagency effort. The Federal Water Master appointed by the *Orr Ditch* court oversees and coordinates reservoir operations for the delivery of water for *Orr Ditch* decree water rights, as well as maintains a water accounting system and issues daily reports of hydrologic data measurements. Reclamation has the authority and responsibility for managing the principal water storage facilities on the Truckee River system, including implementing scheduled releases, implementing dam safety and flood control requirements, administering water storage contracts, forecasting inflows and releases, generating power, developing operation plans, and regulating diversions at Derby Dam under the Operating Criteria and Procedures. The Nevada State Engineer has primary jurisdiction over applications to change the manner, purpose, or place of use of water rights subject to the *Orr Ditch* decree. The California State Water Resources Control Board is responsible for the administration of post-1914 appropriative water rights in California. The Federal reservoirs are operated in accordance with flood control criteria from USACE.

The Truckee River is a highly regulated river system. Dams at the outlet of Lake Tahoe and on several major tributaries in the Truckee River basin create reservoirs that together can store about a million acre-feet of water. The reservoirs are operated to capture runoff as available when flow in the river is greater than that needed to serve downstream water rights in Nevada and to maintain prescribed streamflows, known as Floriston Rates, in the Truckee River measured at the Farad gauge near the California-Nevada State line. Floriston Rates provide water to serve hydroelectric power generation, municipal and industrial (M&I) use in Truckee Meadows, streamflow, and agricultural water rights. In general, reservoir releases are made as necessary to meet dam safety or flood control requirements and to serve water rights when unregulated flow cannot be diverted to serve those rights. Minimum reservoir releases are maintained as specified in applicable agreements and the reservoir licenses and/or permits.

There are five Federal reservoirs and two privately owned reservoirs located in the upper reaches of the Truckee River in California. Donner and Independence Lakes are privately owned natural mountain lakes, which have small dams controlling water storage above the natural rim of the lakes. Independence Lake is operated to supplement M&I use for the cities of Reno and Sparks. Donner Lake is operated for lake-related recreation, to supplement M&I use for the cities of Reno and Sparks, and for irrigation on the Newlands Irrigation Project near Fallon, Nevada. Martis Reservoir is a small flood control reservoir owned by USACE. Lake Tahoe, Prosser Creek Reservoir, Stampede Reservoir, and Boca Reservoir are all Reclamation facilities used to provide storage for agricultural irrigation and M&I use as well as water for the preservation of endangered fish in

Pyramid Lake. Like Donner and Independence Lakes, Lake Tahoe was originally a natural lake and now has a small dam controlling storage above the natural rim of the lake. Lake Tahoe is the tenth deepest lake in the world, at approximately 1,650 feet deep. It is known for its natural beauty, cobalt-blue color, and clarity, which stems from its characteristics as a low-nutrient (ultra-oligotrophic) lake. However, long-term monitoring shows Secchi depth transparency has declined by 10 meters since 1968, the rate of carbon primary productivity continues to increase 5% per year, and thick growths of algae cover portions of the once-pristine shoreline.

There are two large structures on the middle and lower reaches of the main stem of the Truckee River. These are Derby Diversion Dam and Marble Bluff Dam. Derby Diversion Dam is located downstream from Reno and diverts water out of the Truckee River into the Truckee Canal to provide irrigation water for a portion of Reclamation's Newlands Project along the Truckee Canal near the city of Fernley, Nevada. Additionally, water taken from the Truckee at Derby Dam flows through the Truckee Canal out of the basin into Lahontan Reservoir on the Carson River and is used to irrigate agricultural lands in Reclamation's Newlands Project within the Carson basin as well as to supply water to a national wildlife refuge and the Fallon Paiute Shoshone Indian Reservation. Marble Bluff Dam was constructed to check the downcutting and erosion of the river channel upstream of Pyramid Lake.

Pyramid Lake is a large closed-basin lake about 40 miles northeast of Reno and is the terminus for the Truckee River. It is 15 miles long, 11 miles wide, and 350 feet deep. Pyramid Lake is the deepest terminal saline lake in the Western Hemisphere and is the only large closed-basin lake to survive desiccation during the Holocene (Mensing et al. 2003). Pyramid Lake levels strongly reflect climatic conditions in the northern Sierra Nevada (Briggs et al. 2005). During the Pleistocene, pluvial Lake Lahontan covered 22,000 km^2; Pyramid Lake is the largest remnant of Lake Lahontan and currently covers 450 km^2 (112,000 acres). The lake is home to two fish that are on the Federal threatened and endangered species list, the cui-ui and the Lahontan cutthroat trout.

8.2 Historical Climate

The Truckee River headwaters lie along the eastern slope of the Sierra Nevada. Snowpack represents up to 80% of the entire year's precipitation in the basin and normally provides for year-round flow (Lea 2010). Over the course of the 20^{th} century, warming has been prevalent over the Truckee River basin. Basin average mean-annual temperature has increased by approximately 2 °F for an area encompassing the Truckee River and Carson River basins (figure 58). However, throughout much of the period of record, large variations in annual temperature have been observed.

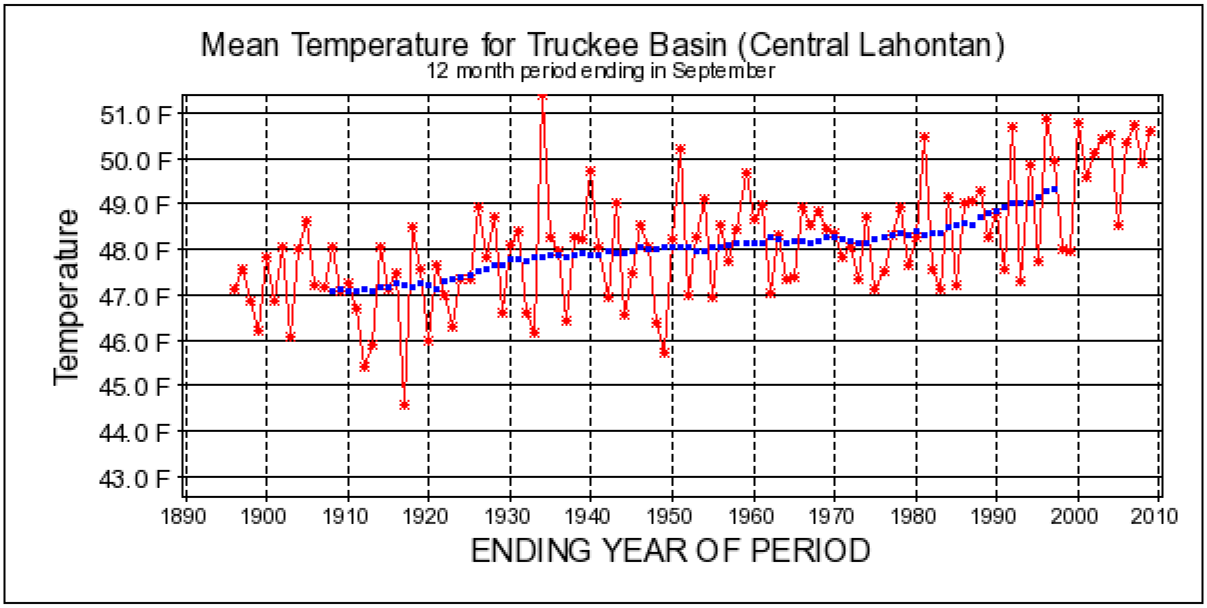
The pace of warming has not been steady in time throughout the 20th century. As depicted within figure 58 (top panel), the region's average temperature increased steadily from the beginning of the 20th century to the 1930s; but then from the 1930s to the 1970s, it generally remained unchanged. However, since the 1970s, basin average temperature has again been steadily increasing.

The temperature changes described in the previous paragraph is consistent with another study of regional climate trends in the Lake Tahoe basin (Coats 2010), which reported that the strongest upward trends in annual averages were for maximum temperature in Reno and for minimum temperature in Tahoe City. Truckee and Boca also showed significant upward trends for both maximum and minimum temperatures. Warming rates were found to be lower in summer and minimal in fall for Truckee and Boca. The strongest warming trends from 1956–2005 were minimum temperatures in Reno and Tahoe, especially during summer.

Region annual precipitation has fluctuated considerably during the past century (figure 58, bottom panel), generally varying between 6–20 inches. Relative to annual temperature, any trend in mean-annual precipitation during the period of record seems less apparent. Other studies have focused on local precipitation trends. Coats (2010) reported that total annual precipitation at Tahoe City has been trending slightly upward at 0.13% per year; however, total annual precipitation falling as snow has decreased about 0.19% per year. They also report that frequency of intense rainfall was found to be increasing, which suggested a corresponding increase in rain-on-snow events.

Fossil pollen in sediment cores from Pyramid Lake encompassing the last 7,500 years was examined by Mensing et al. (2003) who concluded the mid-Holocene (7500-6300 years before present [BP]) was the warmest and driest period in that time. Mensing et al. (2003) suggest that Lake Tahoe was below its rim for most of this period, greatly reducing the size of Pyramid Lake at that time.

The pollen record indicates a shift to a wetter climate in 6300 BP; but as whole, the data indicates the dry period for the area did not end until about 5000 BP. A gradual increase in precipitation resulted in a wetter climate through about 3500 BP. Very dry conditions returned between 2500–1800 BP. The past 1,800 years have experienced wet and dry cycles, but none of the dry periods matched the intensity of earlier periods. The record indicates extended droughts occurred between 1500–1250 BP, 800–725 BP, and 600–450 BP.



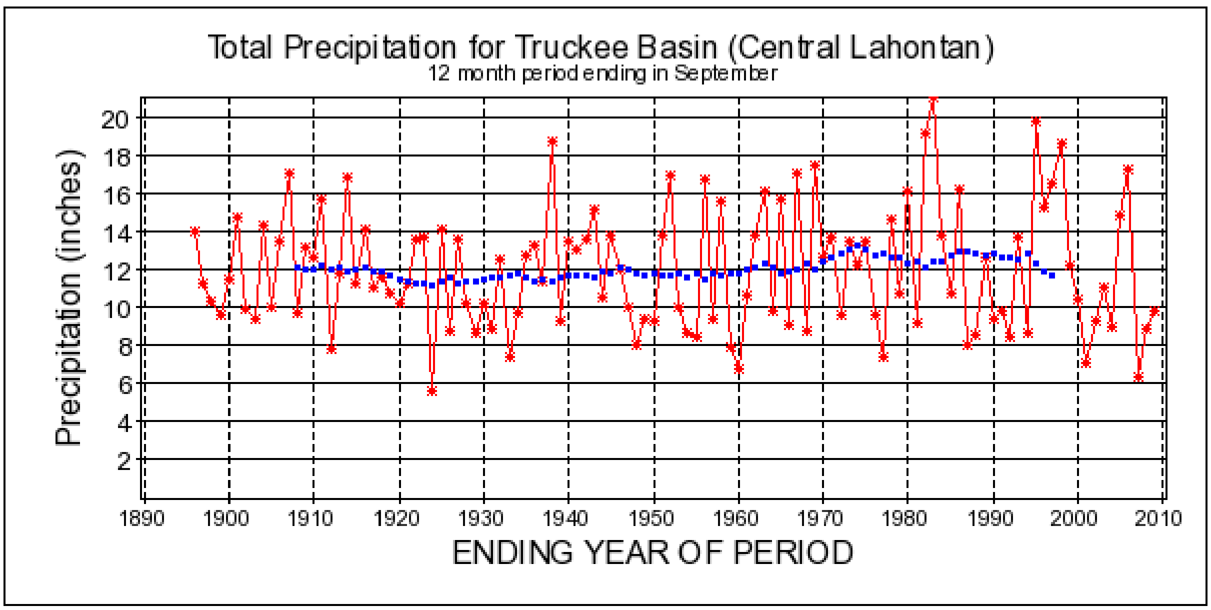


Figure 58. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Truckee River region.

Source: Western Climate Mapping Initiative (WestMap) available at: http://www.cefa.dri.edu/ Westmap/. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 2004; Gibson et al. 2002).

8.3 Historical Hydrology

Historical runoff in the Truckee River basin tends to vary considerably from year to year. Geographic variation in runoff is generally less pronounced in the Truckee River basin than in the other larger basins considered in this report (e.g., Columbia, Colorado, Missouri). This is because the Truckee River basin tends to experience seasonal climate that is generally consistent across the basin; the larger basins span a large enough region that seasonal climate can vary within those larger basin boundaries. A review of historical information in the Truckee River basin shows that some runoff trends within the basin may be apparent depending on location and historical period that's analyzed. However, evaluation of trends in historic hydrology suggests that they are relatively weak to insignificant.[10] This finding is consistent with other recent analysis on Truckee River annual runoff trends (Lea 2010).

Coincident with the climate trends discussed in the previous section, the Truckee River and Carson River basins generally have experienced a general decline in spring snowpack, reduced snowfall to winter precipitation ratios, and earlier snowmelt runoff between the mid- and late-20th century. Various studies have reported trends of this nature. For example, Lea (2010) reports that, since 1980, there has been a decrease in the April 1st snowpack compared to seasonal precipitation indicating more rain than snow and/or that the snow is melting earlier. Another study (Coats 2010) reported that, in five Lake Tahoe basin streams, snowmelt peak was found to shift earlier by 0.4 days per year from 1961 to 2005. Snow water equivalent at Tahoe City was found, statistically, to have decreased 0.19% per year from 1910–2005. It has been suggested that these findings indicate Lake Tahoe basin is warming faster than surrounding areas.

Trends toward less snow accumulation and earlier melt at elevations below 2400 meters and toward higher accumulations and earlier melt at higher elevations were identified by Johnson et al. (1999). They also found Lake Tahoe basin had the highest May snow water equivalent loss of any of the 21 basins studied in the Sierra Nevada over the 1966-1996 period of record.

Several studies suggest that many observed trends for snow water equivalent, soil moisture and runoff in the Western United States are the result of increasing

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[10] Trend significance was assessed using statistical testing during the period of 1951–1999 applied to historical simulated runoff results under observed historical weather conditions (Reclamation 2011a). Trends were computed and assessed for four Truckee basin locations, focusing on annual and April–July runoff. In all cases, computed trends were judged to not be statistically significant with 95% confidence.

temperatures rather than precipitation effects (Lettenmaier et al. 2008). Still, any such apparent trends or changes over regional drainages such as the Truckee River basin are sensitive to the uncertainties of station measurements as well as the period of analysis and location being analyzed. Relating to the broader Western United States, historical trends in Western United States temperature, precipitation, snowpack, and streamflow might be partially explained by anthropogenic influences on climate (e.g., Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009), but it remains difficult to attribute historical trends in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends in precipitation (Hoerling et al. 2010) and for trends in basin-scale conditions rather than at the Western United States conditions (Hidalgo et al. 2009).

8.4 Future Changes in Climate and Hydrology

While the previous section focused on historical conditions, this section summarizes results from studies focused on future climate and hydrologic conditions within the Truckee River basin. Discussion first focuses on results from Reclamation (2011a), which were produced within the context of a west-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the eight major river basins identified within the SECURE Water Act. These results are discussed separately from those of other studies to set up easier comparison with future climate and hydrology results found in the other basins reported on in this document.

8.4.1 Projections of Future Climate and Hydrology

This section initially summarizes climate projections and climate change assumptions featured within Reclamation (2011a). Climate information is first presented from the perspective of basin-average and, secondly, as those climate conditions are distributed throughout the basin. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented. Finally, climate and snowpack changes translated into effects on annual and seasonal runoff, as well as acute runoff events relevant to flood control and ecosystems management are discussed.

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections' median condition through time, results suggest that temperatures throughout the Truckee River and Carson

River basins may increase steadily during the 21st century (figure 59). Focusing on the Truckee River above Nixon gauge, the basin-average mean-annual temperature is projected to increase by approximately 5–6 °F during the 21st century, with the range of annual possibility widening through time.

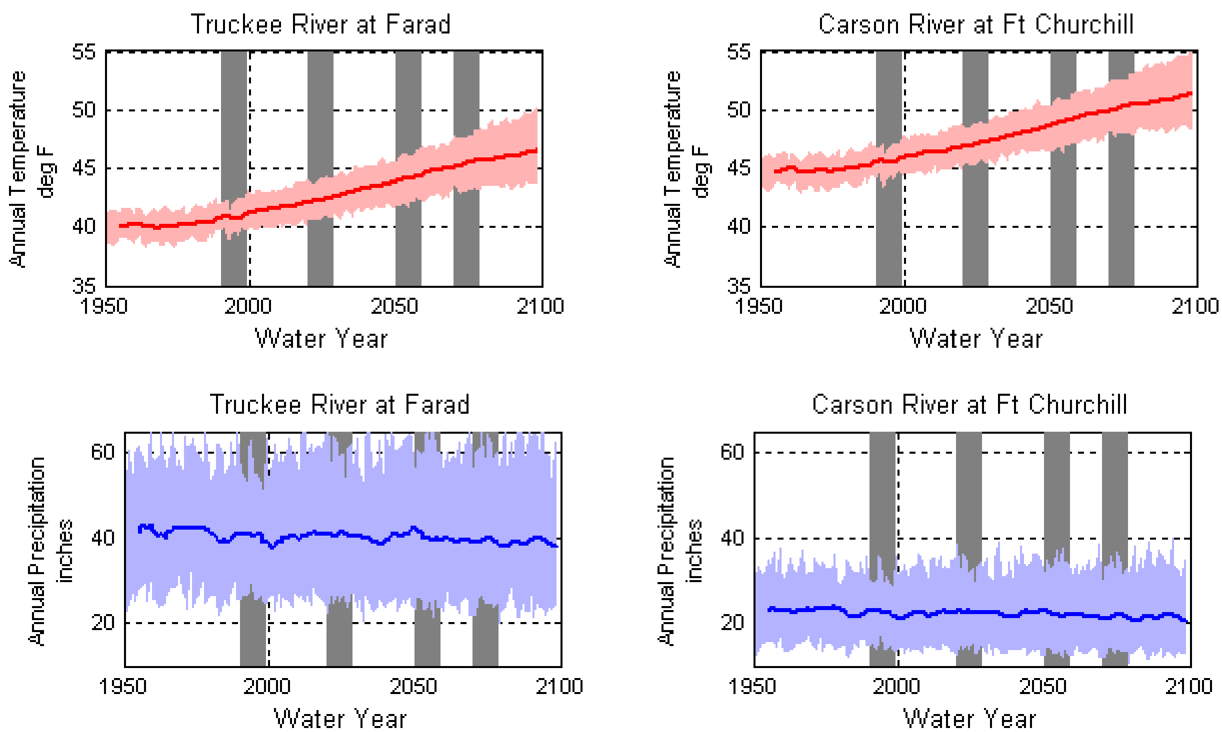

Figure 59. Simulated annual climate averaged over Truckee and Carson River subbasins.

Figure 59 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections (section 1.5.1). Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations (section 1.5.1), and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

A similar trend is found for projected temperatures averaged over the Carson River above Fort Churchill gauge. The same climate projections suggest that mean-annual precipitation, averaged over either subbasin (figure 59), is projected to remain relatively unchanged or to decrease slightly during the 21st century. This is evident by following the ensemble median of the annual precipitation through time for both basins, noting that the condition remains relatively static during the early 21st century and then slightly decreases during the last half of the 21st century.

Some geographic complexities of climate changes can be observed over the Truckee River basin when climate projections are inspected location by location. For example, consider the four decades highlighted on figure (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s are considered here to be the baseline climate from which climate changes will be assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, annual average temperatures are generally cooler along the western mountainous rim of the basin (figure 60, top left panel). Warmer temperatures are observed in lower lying areas to the east. Likewise, precipitation is generally greater in the higher elevations to the west, particularly along the mountainous rim, and lesser over of the eastern lowlands (figure 61, top left panel). Regarding climate change, temperature changes are generally uniform over the basin, steadily increasing through time (figure 59). For precipitation, similar geographic uniformity is found (figure 60). One contrast from temperature is that the sign of precipitation change varies through the decades, with slight increases projected for the 2020s transitioning to slight decreases by the 2070s.

As climate changes in the 21st century, hydrology is expected to be affected in various ways including snowpack development. As noted previously, warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify this impact on snowpack, it is apparent that warming trends in the Truckee River basin tend to dominate expected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on figure 62). Decreases in snowpack are expected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. This is particularly true for the lower elevation areas in the middle and eastern portions of the basin.

As the effects of climate change and snowpack are realized throughout the Truckee River basin, these effects will drive changes in the availability of natural water supplies. These effects may be experienced in terms of changes to annual runoff, and also changes in runoff seasonality. For example, warming without precipitation change would lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) would serve to offset or amplify this impact. Results from Reclamation (2011a) suggest that annual runoff effects are generally consistent throughout the Truckee River and Carson River basins (figure 62), with little projected change in annual runoff. However, it is noted that these results are

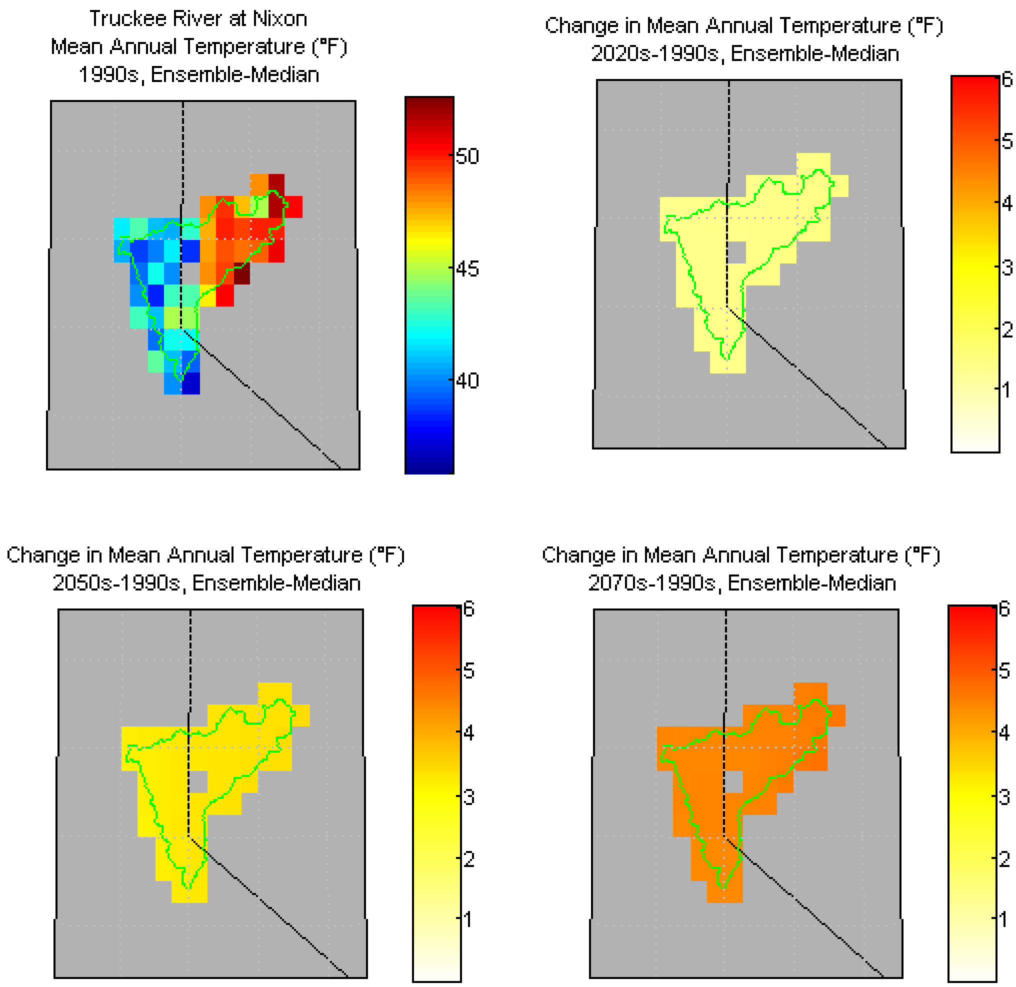

Figure 60. Simulated decade-mean temperature over the Truckee River basin above Nixon.

Figure 60 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

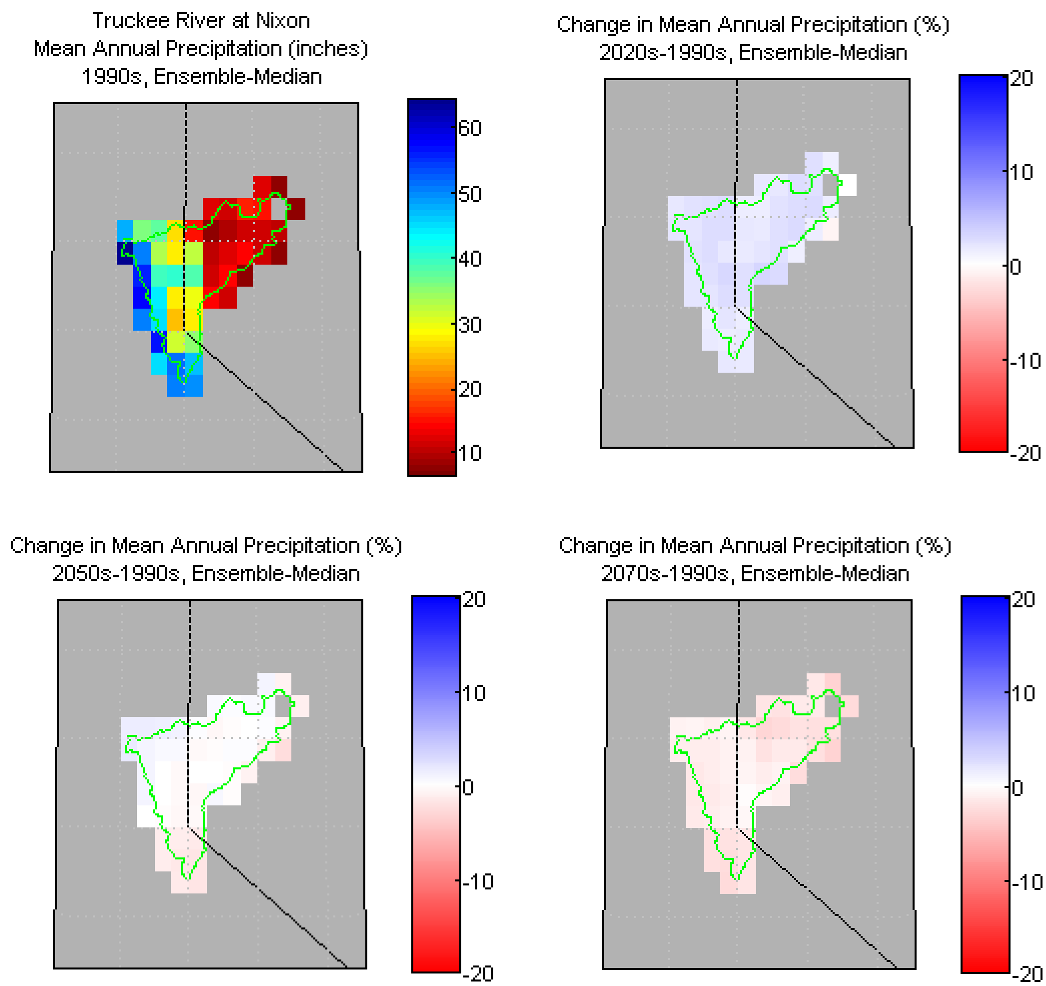

Figure 61. Simulated decade-mean precipitation over the Truckee River basin above Nixon.

Figure 61 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

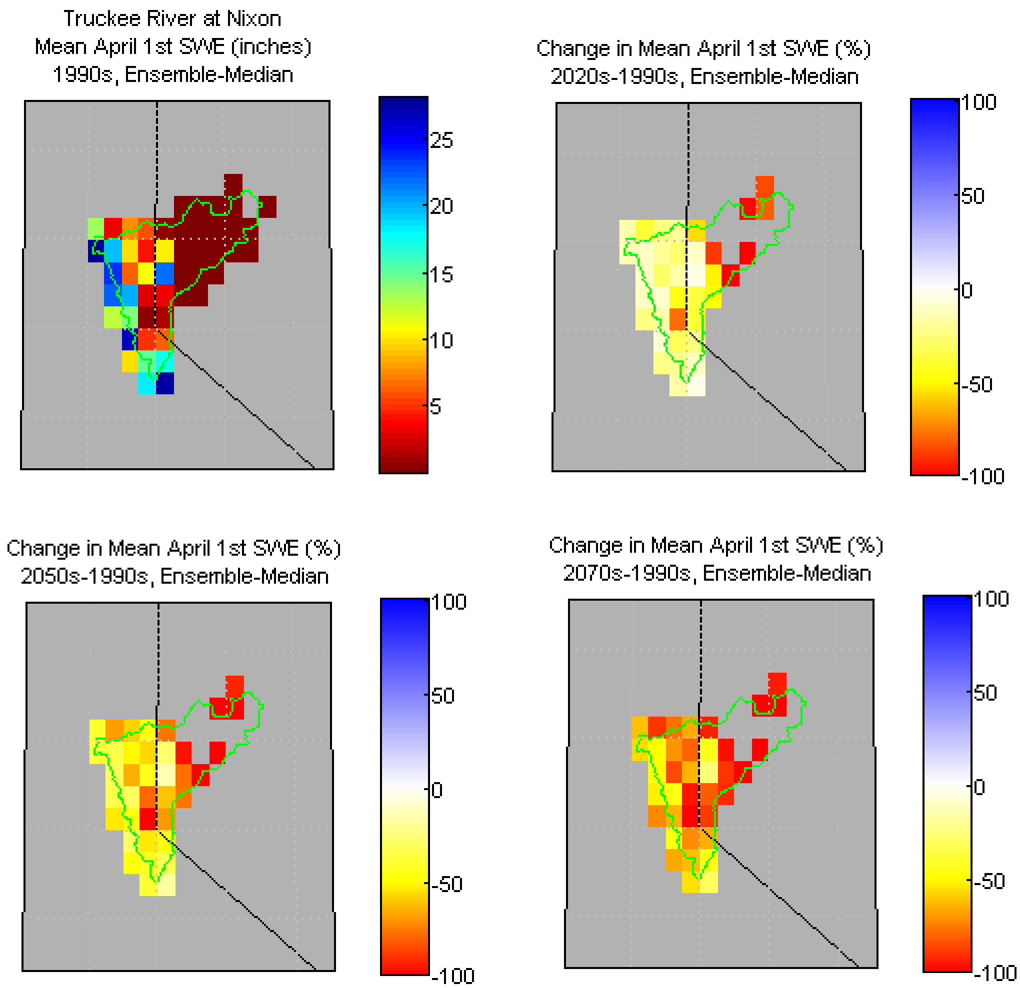

Figure 62. Simulated decade-mean April 1st snowpack over the Truckee River basin above Nixon.

Figure 62 presents basin-distributed views of change over the given basin and variable. Figure data are simulated conditions as described in Reclamation 2011a. Upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations (section 1.5.1). Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

based on use of a hydrologic model that only offers a simplistic portrayal of Lake Tahoe evaporation losses and may not sufficiently represent lake evaporation impacts under warming conditions.

The seasonality of runoff also is projected to change. Warming is expected to lead to more rainfall-runoff during the cool season rather than snowpack accumulation. This conceptually leads to increases in December–March runoff and decreases in April–July runoff. Results suggest that these concepts generally hold for the Truckee River and Carson River basins; however, the degree to which these effects are projected varies by subbasin (figure 63). Focusing on December–March seasonal runoff, results show an increased mean seasonal volume by the 2020s and a trend toward greater increases by the 2070s in all of the subbasins. Focusing on April–July seasonal runoff, results show declines in April–July runoff, as projected warming leads to not only spring snowpack decline (figure 62) but with a corresponding reduction in spring–summer runoff. It may be noticed that percentage reductions in April–July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April–July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April–July runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to acute runoff events relevant to Truckee River flood control and ecosystem management is also of high interest, although there is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. Utilizing annual maximum- and minimum-week runoff as metrics of acute runoff events, respectively (figure 63), it appears that results are generally consistent across Truckee River and Carson River subbasins.

Focusing on annual maximum-week runoff events, results suggest generally steady to slightly decreasing expected annual condition during the 21st century, but perhaps with an expanding range of possibility. Such results suggest future hydroclimate conditions may produce weekly flows that have a wider range of variability..

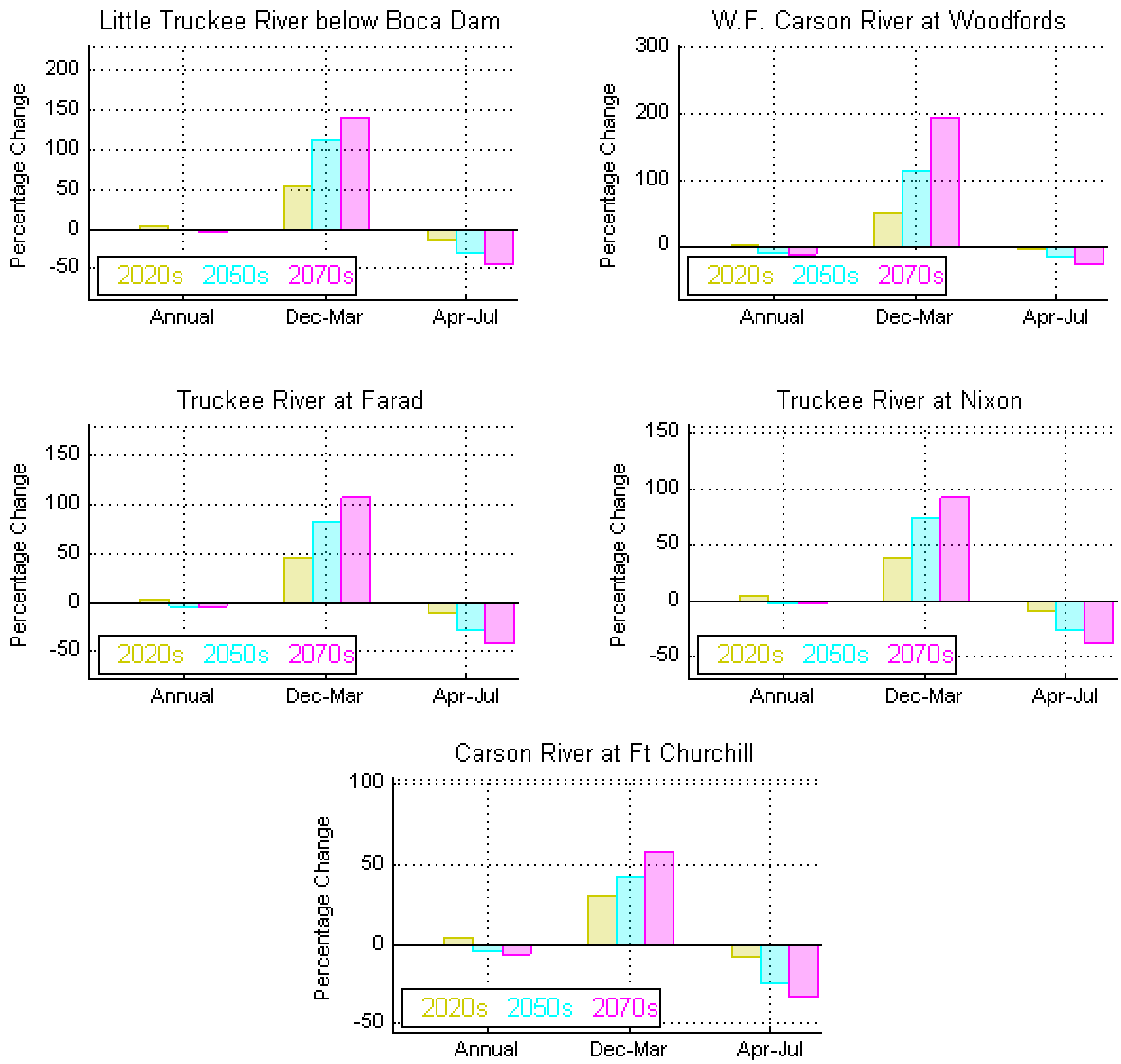

Figure 63. Simulated changes in decade-mean runoff for several subbasins in the Truckee and Carson River basins.

Figure 63 presents annual, December–March, and April–July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1).

Focusing on annual minimum-week runoff events, results suggest gradual decline during the 21st century, with diminishing annual variability. Decreasing minimum runoff may result in reduced capacity for diversions for agricultural, municipal, and industrial uses. Decreasing minimum runoff also adversely affects aquatic habitats by both reducing wetted stream perimeters and availability of aquatic habitat and through increased water temperatures detrimental to temperature-sensitive organisms. Since much of the water stored in the basin is used to support fisheries, the downward trend in both maximum and minimum runoff may result in earlier reservoir evacuations to meet these requirements. However, in spite of these findings, it is noted that to truly understand potential changes in acute runoff events such as these, and implications of such changes for reservoir management in the Truckee River basin, more indepth analyses are warranted.

A summary of climate and hydrologic changes is provided in table 7 for three subbasins of the Truckee River and Carson River basins: Truckee River at Farad gauge, Truckee River at Nixon gauge, and Carson River at Fort Churchill gauge. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

8.4.2 Other Studies of Future Climate and Hydrology

Results from Reclamation (2011a) are broadly consistent with previous studies on climate change and hydrologic impacts over the basin. For example, another study (Coats 2010) evaluated a collection of current climate projections over the region and report that future hydroclimate conditions would feature upward trends in maximum and minimum temperatures, no strong trend for precipitation, continuation of the shift from snowfall to rain in winter, reduced accumulation of snowpack, earlier snowmelt, reduced spring-summer runoff, declining 5-day low flows, increased drought severity especially towards the end of the century, and increases in flood magnitude by mid-century. They also suggest that temperatures in the vicinity of Lake Tahoe would rise 2.5–4 °C (4.5–7.2 °F) with drying trends of 10–20 centimeters (3.9–7.8 inches) per year per century over the Sierra Nevada, including Lake Tahoe (Coats 2010). This level of warming and drying would be equivalent to moving the lake from 1,900–1,130 meters (6,230–3,710 feet), with significant effects on lake temperature, lake communities, and climax terrestrial vegetation in the basin. Complete drying of lower reaches of basin streams is projected to increase with drying and warming conditions.

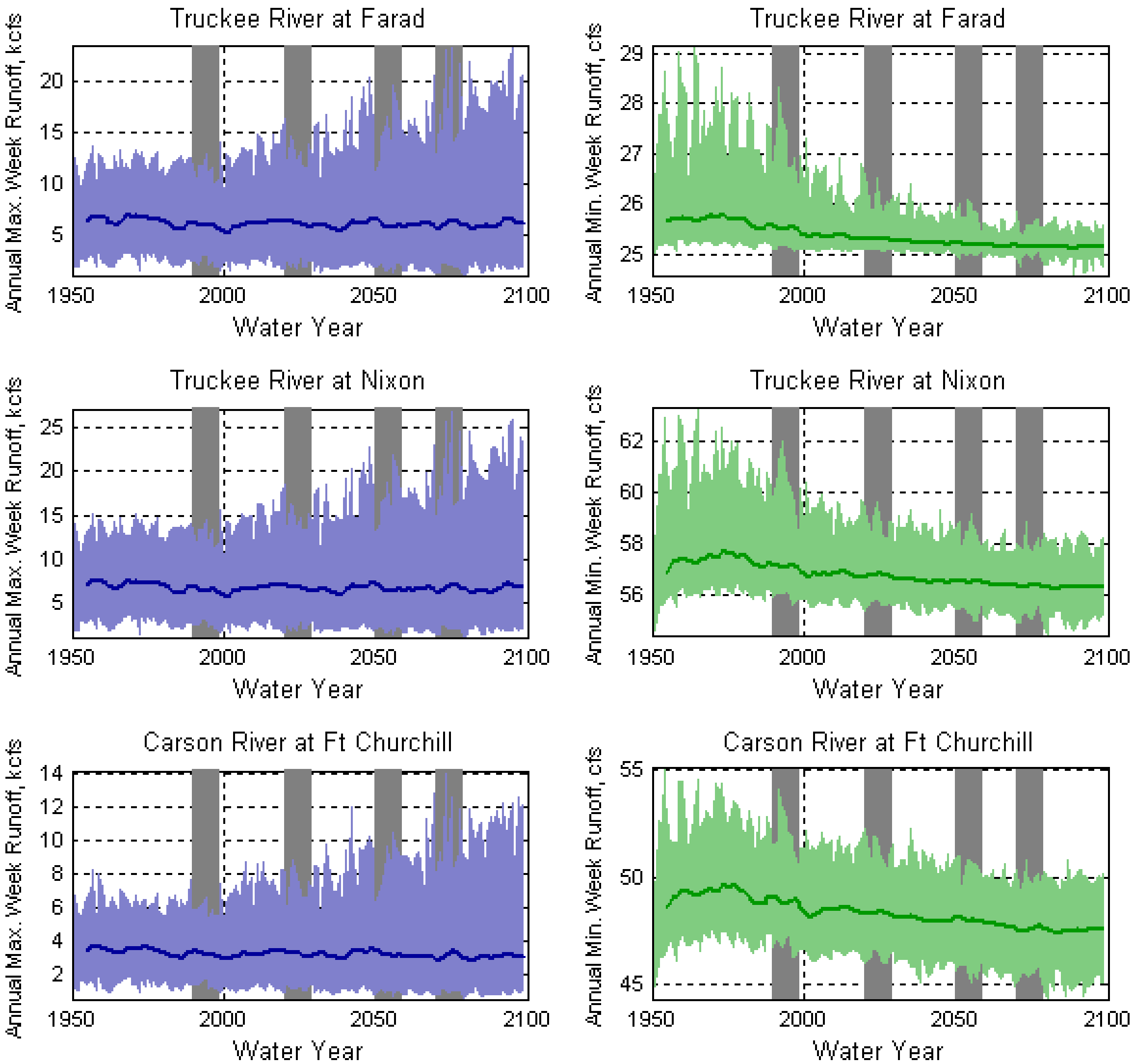

Figure 64. Simulated annual maximum and minimum week runoff for several subbasins in the Truckee and Carson River basins.

Figure 64 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed (section 1.5.1). It should be noted that these results are derived from simulations that have been computed at a daily time step, but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis.

Table 7. Summary of simulated changes in decade-mean hydroclimate for several subbasins in the Truckee and Carson River subbasins

Hydroclimate Metric (Change from 1990s)	2020s	2050s	2070s
Truckee River at Farad			
Mean Annual Temperature (°F)	1.5	3.3	4.5
Mean Annual Precipitation (%)	0.8	-0.3	-3.0
Mean April 1st Snow Water Equivalent (%)	-22.0	-46.3	-63.1
Mean Annual Runoff (%)	3.8	-2.8	-3.1
Mean December–March Runoff (%)	46.7	82.4	106.4
Mean April–July Runoff (%)	-10.0	-27.2	-40.5
Mean Annual Maximum Week Runoff (%)	2.6	0.8	2.4
Mean Annual Minimum Week Runoff (%)	-0.9	-1.2	-1.4
Truckee River at Nixon			
Mean Annual Temperature (°F)	1.5	3.3	4.5
Mean Annual Precipitation (%)	0.6	-0.7	-3.1
Mean April 1st Snow Water Equivalent (%)	-40.4	-60.5	-73.1
Mean Annual Runoff (%)	4.3	-2.5	-2.5
Mean December–March Runoff (%)	38.8	72.9	90.8
Mean April–July Runoff (%)	-8.5	-25.9	-37.6
Mean Annual Maximum Week Runoff (%)	3.3	1.3	2.7
Mean Annual Minimum Week Runoff (%)	-0.6	-1.0	-1.3
Carson River at Fort Churchill			
Mean Annual Temperature (°F)	1.5	3.4	4.6
Mean Annual Precipitation (%)	0.1	-1.6	-4.7
Mean April 1st Snow Water Equivalent (%)	-49.6	-66.1	-75.8
Mean Annual Runoff (%)	4.1	-4.5	-6.1
Mean December–March Runoff (%)	30.1	41.7	57.5
Mean April–July Runoff (%)	-7.9	-23.9	-32.4
Mean Annual Maximum Week Runoff (%)	-0.4	-0.9	-3.3
Mean Annual Minimum Week Runoff (%)	-1.1	-1.8	-2.7

8.5 Future Implications for Water and Environmental Resources

8.5.1 Water Supply, Reservoir Operations and Flood Management

Based on current reservoir operational constraints (e.g., storage capacity, constraints on reservoir water releases to satisfy various obligations), projected effects on runoff seasonality from warming without precipitation change would lead to reduced water supplies within the Truckee River basin. This expectation is based on current operating conditions that limit storage opportunities during the winter runoff controlled by flood control considerations, and that increased winter runoff under climate change will not necessarily translate into increased storage of water leading into the spring season. Capture of snowmelt runoff traditionally has occurred during the late spring and early summer seasons. Reductions in runoff during the spring and early summer season likely would translate into reductions in storage capture and likewise reductions in water supply for warm season delivery.

8.5.2 Hydropower

Electricity demand, from hydropower generation and other sources, generally correlates with temperature (Scott and Huang 2007). For example, demand for heating increases during cooler days, and demand for air conditioning increases during warmer days. Hydroelectric generation to satisfy demands is sensitive to climate changes that may affect basin precipitation, river discharge (amount and timing), and reservoir water levels. Hydropower operations also are affected indirectly when climate change affects air temperatures, humidity, or wind patterns (Bull et al. 2007). Climate changes that result in decreased reservoir inflow or disrupt traditional timing of inflows could adversely impact hydropower generation. Alternatively, increases in average flows would increase hydropower production.

8.5.3 Fish and Wildlife

Projected climate changes are likely to have an array of interrelated and cascading ecosystem impacts (Janetos et al. 2008). At present, most projected impacts are primarily associated with increases in air and water temperatures and include increased stress on fisheries that are sensitive to a warming aquatic habitat, potentially improved habitat for quagga mussels bearing implications for maintenance of hydraulic structures, and increased risk of watershed vegetation disturbances due to increased fire potential. Seasonal hydrologic changes associated with warming also could affect fisheries. For example, seasonal runoff changes in the Truckee River may affect reproductive strategies for cui-ui and Lahontan cutthroat trout further complicating efforts to restore these imperiled fish species. Other warming-related impacts include impacts on the arrival and departure of migratory species, amphibian population declines, and effects on pests and pathogens in ecosystems. Climate change can also trigger synergistic effects in ecosystems and exacerbate invasive species problems.

8.5.4 Water Quality

Whether water quality conditions improve or deteriorate under climate change depends on several variables, including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed (Lettenmaier et al. 2008). Climate change has the potential to alter all of these variables. Climate change impacts on surface water ecosystems very likely will affect their capacity to remove pollutants and improve water quality; however, the timing, magnitude, and consequences of these impacts are not well understood (Lettenmaier et al. 2008). Increased summer air temperatures could increase dry season aquatic temperatures and affect fisheries habitat.

Water quality conditions are a significant consideration in the land and water management within the Lake Tahoe basin. Data from Lake Tahoe shows that since 1968, the lake mixes completely to the bottom about every 4 years. Based on one climate projection scenario for the mid-21st century (Coats 2010), results suggest that Lake Tahoe could cease to mix to the bottom (500 meters), with the density difference between warm and cold water becoming too great for wind energy to overcome. Absent complete mixing, bottom waters are not replenished with oxygen and become depleted. Under these anoxic conditions, soluble reactive phosphorus and ammonium-nitrate are released from lake sediments increasing nutrient loading. This would be a new and significant source of nutrients in the system. Intermittent periods of oxygen depletion are expected in the deepest waters within the next 20 years. Loading of soluble phosphorus is expected to double current loading rates. Loading of ammonium-nitrate is expected to increase available nitrogen by 25%. Such an effect as increased nutrient loading to Lake Tahoe could have dramatic and long-lasting impacts on the food web, species and community composition, and trophic status (Coats 2010).

8.5.5 Ground Water

Land resources may be affected by climate change (Ryan et al. 2008), and depletions to natural ground water recharge are sensitive to climate warming (Lettenmaier et al. 2008). Additionally, reduced mountain snowpack, earlier snowmelt, and reductions in spring and summer streamflow volumes originating from snowmelt likely would affect surface water supplies and could trigger heavier reliance on ground water resources. However, warmer, wetter winters could increase the amount of water available for ground water recharge, but this area needs further study.

8.5.6 Water Demands

Potential climate changes to agricultural, municipal and industrial, and instream water demands are difficult to project; and existing information on the subject is limited. It is widely accepted in the literature that water demands will change due to increased air temperatures; increased atmospheric carbon dioxide levels; and changes in precipitation, winds, humidity, and atmospheric aerosol and ozone levels. Further, these natural system changes must be considered in combination with socioeconomic changes, including infrastructure, land use, technology, and human behavior.

Agricultural water demands include those associated with crop irrigation and livestock consumption. Given that the atmosphere's moisture holding capacity increases when air temperature increases, it seems intuitive that plant water consumption and surface water evaporation associated with agricultural demands will increase in a warming climate. However, it is understood that crop water needs respond to not only temperature and precipitation conditions but also atmospheric carbon dioxide, ozone, and potential evapotranspiration (e.g., Baldocchi and Wong 2006; Bloom 2010), which the latter is affected by solar radiation, humidity, and wind speed. Additionally, agricultural water demand could decrease due to crop failures caused by pests and disease exacerbated by climate change. The seasonal volume of agricultural water demand could increase if growing seasons become longer; assuming that farming practices could adapt to this opportunity by planting more crop cycles per growing season. This possibility is based on studies suggesting that the average North American growing season length increased by about 1 week during the 20th century; and it is projected that, by the end of the 21st century, it will be more than 2 weeks longer than typical of the late 20th century (Gutowski et al. 2008). Another study suggests that agricultural lands requiring irrigation may increase by up to 40% due to climate change, and livestock water demands will increase significantly (Pacific Institute 2009).

Climate change also could result in changed demand for instream flow or reservoir release to satisfy other system objectives, including ecosystem support, hydropower generation, municipal and industrial water deliveries, river and reservoir navigation, and recreational uses. Water demands for endangered species and other fish and wildlife could increase with ecosystem impacts due to warmer air and water temperatures and resulting hydrologic impacts (i.e., runoff timing).

Other consumptive uses associated with reservoir systems management include reservoir evaporation, losses during water conveyance, and onfarm application. These types of system losses can be significant (e.g., evaporation from Lake Tahoe). Reservoir evaporation may increase if warming temperatures override other factors, but other losses may be reduced in the future with more efficient application methods and conveyance improvements.

9. West-wide Summary of Hydroclimate Changes

As identified throughout this report, much of the Western United States has warmed during the 20th century (roughly 2 °F in the basins considered here) and is projected to warm further during the 21st century (figure 2). Central estimates of this continued warming vary from roughly 5–7 °F depending on location. Historical trends for precipitation are less apparent. Projections of future precipitation indicate that the Northwestern and north-central portions of the United States may gradually become wetter while the Southwestern and south-central portions gradually become drier (figure 3). It is noted that these summary statements reflect regionally averaged changes and that projected changes have geographic variation; they vary through time; and the progression of change through time varies among climate projection ensemble members, represented by the median as discussed within section 1.6.2.

These historical and projected changes in climate have implications for hydrology. Warming trends appear to have led to a shift in cool season precipitation towards more rain and less snow, which causes increased rainfall-runoff volume during the cool season accompanied by less snowpack accumulation. Projections of future hydrology (Reclamation 2011a) suggest that warming and associated loss of snowpack will persist over much of the Western United States (figure 65). However, not all locations are projected to experience similar changes. Analyses suggest that losses to snowpack will be greatest where the baseline climate is closer to freezing thresholds (e.g., lower lying valley areas and lower altitude mountain ranges). Analyses also suggest that, in high-altitude and high-latitude areas, cool-season snowpack actually could increase during the 21st century (e.g., Columbia headwaters in Canada, Colorado headwaters in Wyoming).

Changes in surface water runoff are more complex than projections of snowpack. Analyses of historical runoff suggest that any trends in annual or seasonal runoff are weak. Hydrologic analyses based on future climate projections suggest that geographic trends may emerge (figures 66 and 67). The Southwestern United States to the Southern Rockies may experience gradual runoff declines during the 21st century and the Northwest to north-central United States may experience little change through mid-21st century with increases projected for the late-21st century (figure 66). As presented previously, warming is projected to affect snowpack conditions both in terms of cool season accumulation and warm season melt.

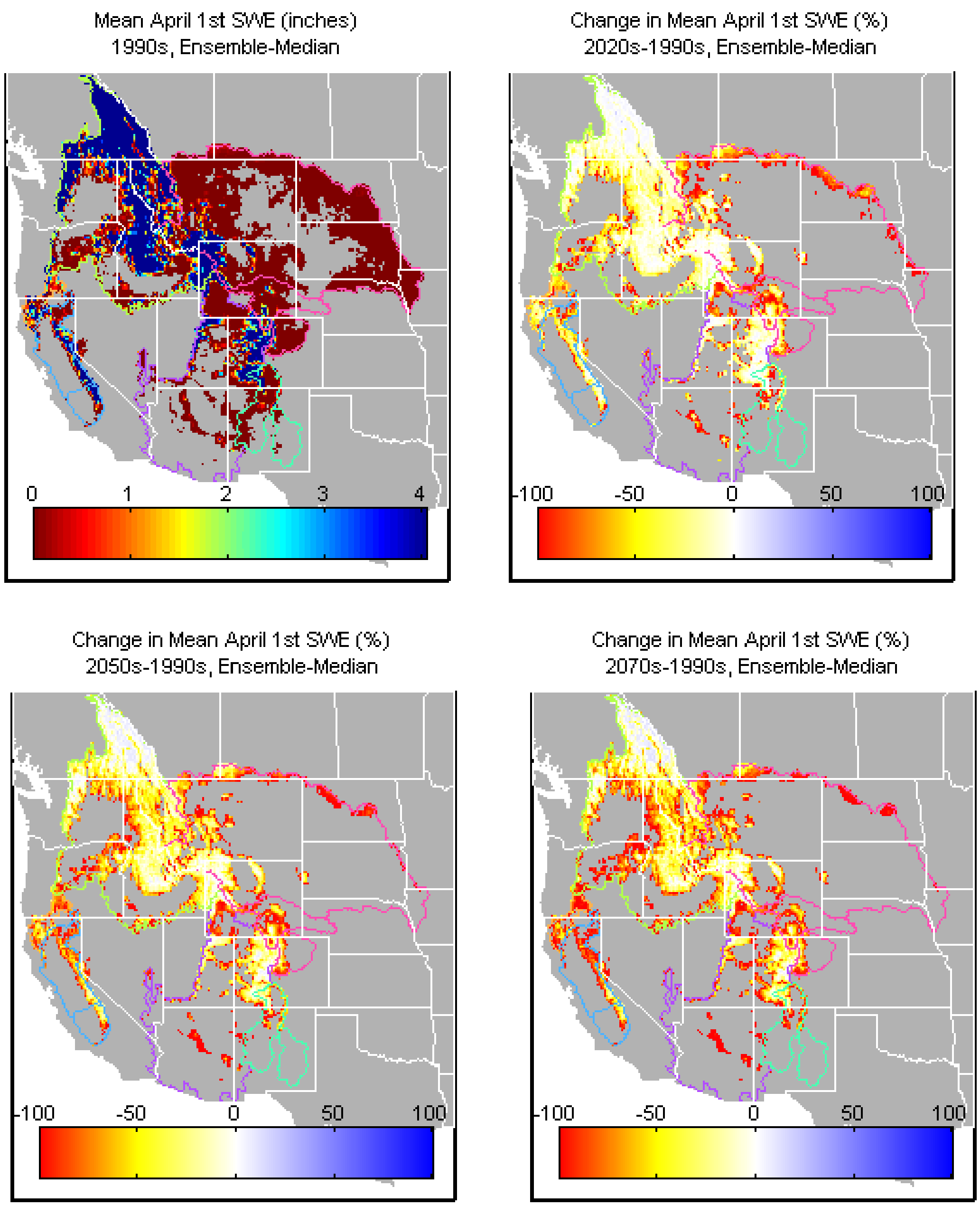

Figure 65. Projected snowpack changes distributed over the West.

Maps show a geographic consolidation of changes already presented in chapters 2–8, based on Reclamation (2011a) simulated hydrologic effects under projected climate change.

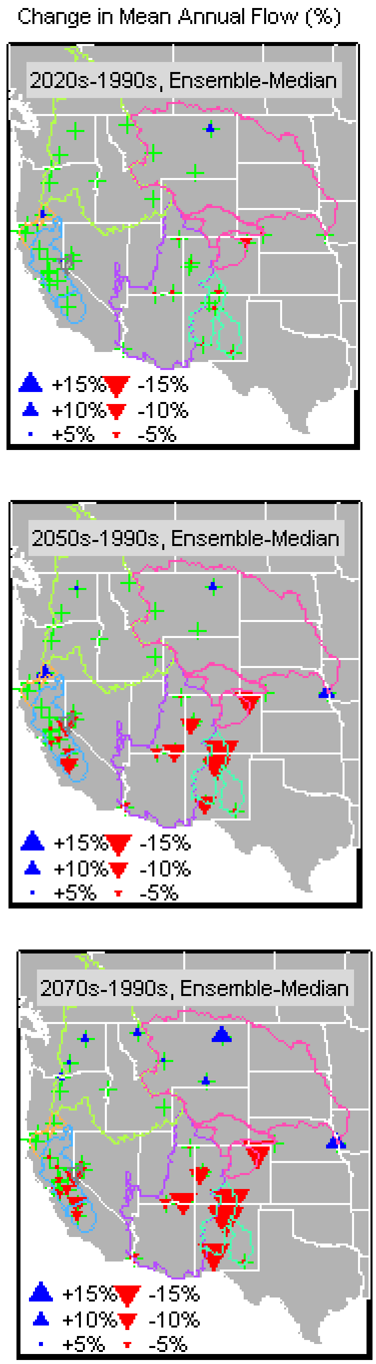

Figure 66. Change in percentage mean annual runoff distributed over the West.

Maps show a geographic consolidation of changes already presented in chapters 2–8, based on Reclamation (2011a) simulated hydrologic effects under projected climate change.

Without changes to overall precipitation quantity, these changes in snowpack dynamics would lead to increases in cool season rainfall-runoff and decreases in warm season snowmelt-runoff. The hydrologic analyses indicate that the degree to which this expectation may occur varies by location in the Western United States (figure 67). For example, cool season runoff is projected to increase over the west coast basins from California to Washington[11] and over the north-central United States, but little change to slight decreases over the Southwestern United States to Southern Rockies is projected. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwestern United States, and Southern Rockies. However, north of this region warm season runoff is projected to change little to slight increases. It seems evident that projected increasing precipitation in the northern tier of the Western United States (figure 3) could counteract warming-related decreases in warm season runoff, whereas projected decreases in precipitation in the southern tier of the Western United States could amplify warming-related decreases in warm season runoff.

[11] Note that December–March runoff results are not shown for the Truckee-Carson basin (figure 67) because of a scale mismatch where the changes for this basin are considerably greater than changes in the other Western United States basins. However, it's noted that the December–March runoff for the Truckee-Carson is projected to increase, consistent with nearby changes in the Sacramento, San Joaquin, and Klamath basins (figure 63).

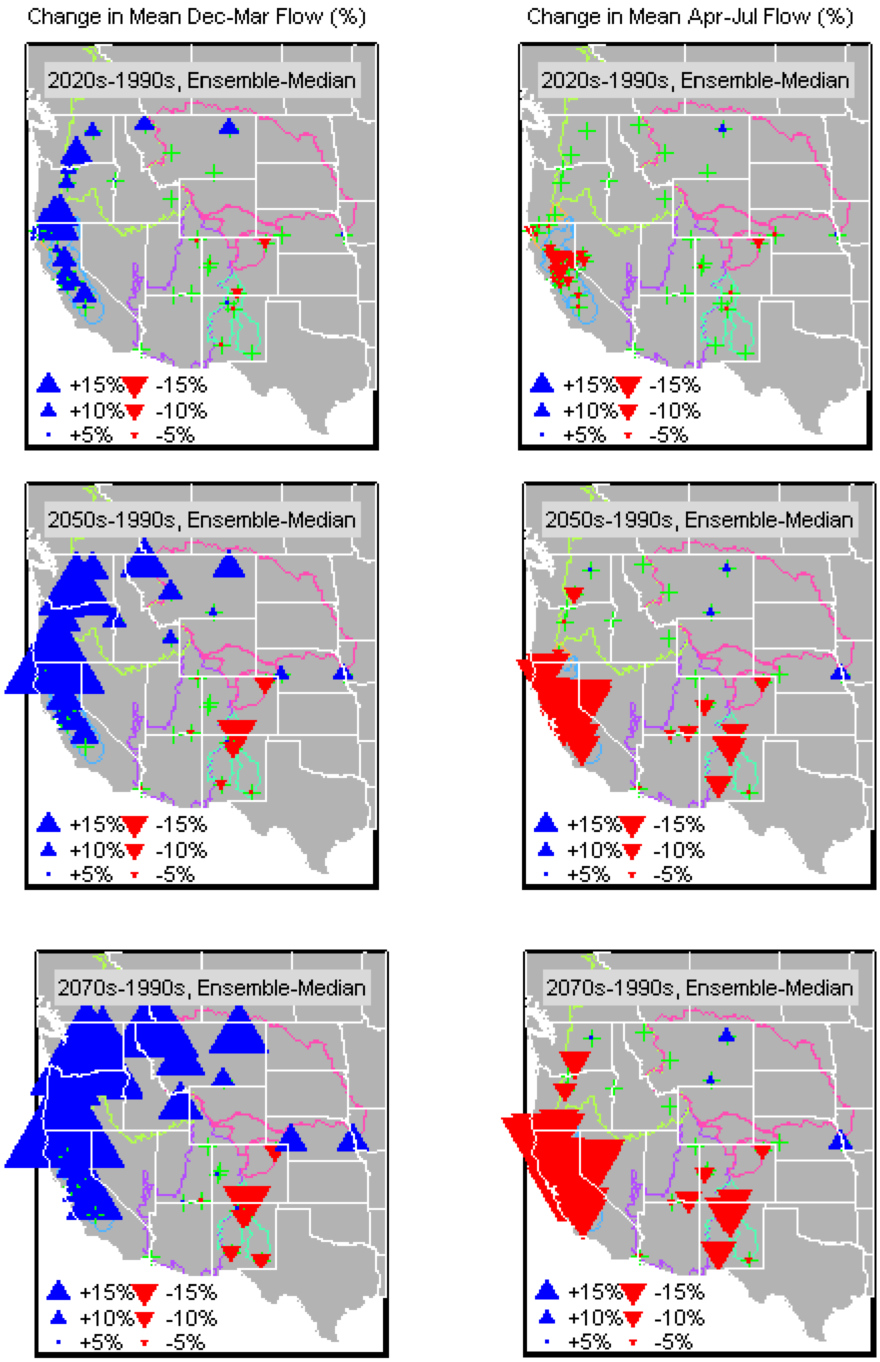

Figure 67. Change in percentage mean December–March and mean April–July runoff distributed over the West.

Maps show a geographic consolidation of changes already presented in chapters 2–8, based on Reclamation (2011a) simulated hydrologic effects under projected climate change.

10. Coordination

In addition to basin specific coordination efforts highlighted throughout this report, Reclamation is coordinating with other Federal and non-Federal agencies to implement Section 9503 of the SECURE Water Act through multiple collaborative approaches, including, the Climate Change and Water Working Group implementation of the Landscape Conservation Cooperatives, supporting the Climate Science Centers; and revision and expansion of the WaterSMART Program to ensure that the most effective conservation and reuse approaches are being employed. Together, these activities will allow Reclamation to better assess the risks and impacts of climate change on the hydrological cycle and to implement collaborative adaptation strategies.

The U.S. Department of Interior participates on the Interagency Climate Change Adaptation Task Force, co-chaired by the Council on Environmental Quality, the National Oceanic and Atmospheric Administration, and the Office of Science and Technology Policy. The Task Force works with Federal agencies to identify actions to better prepare the United States to respond to the impacts of climate change. The October 2010 Progress Report of the Task Force recommends that the Federal Government implement actions to expand and strengthen the Nation's capacity to better understand, prepare for, and respond to climate change. The Task Force's work has been guided by a strategic vision of a resilient, healthy, and prosperous Nation in the face of a changing climate. Reclamation participates on the Water Resources and Climate Change Adaptation Workgroup that supports the Task Force and is developing the National Action Plan for adaptation of freshwater resources management to climate change called for in the October 2010 Progress Report of the Adaptation Task Force (see the October 2010 Progress Report of the Task Force for more information).

In 2008, Reclamation collaborated with the USACE, NOAA, and the USGS to form the CCAWWG to bring water managers and climate scientists together to identify common information gaps that affect capacity to assess, forecast, and adapt to climate change impacts on Western water supplies. Additional CCAWWG Federal participants include the U.S. Environmental Protection Agency, Federal Emergency Management Agency, and National Aeronautics and Space Administration **(**NASA**)**; non-Federal participants include the Western States Water Council; local municipal water authorities; NOAA's Regional Integrated Science and Assessment (RISA) Centers; and the National Center for Atmospheric Research (NCAR).

CCAWWG promotes research collaboration and information sharing among Federal and non-Federal water resource agencies with common climate change goals. In March 2010, the CCAWWG sponsored a workshop to promote collaboration among Federal agencies that were already engaged in climate change studies and efforts involving the Colorado River Basin. Through CCAWWG, Reclamation has also been collaborating with the Department of Energy, Santa Clara University, and ClimateCentral.org to downscale Global Climate Model projections to produce local and regional level climate change impact projections (e.g., impact on temperature and precipitation) to inform Federal and non-Federal water management agencies nationwide. The CCAWWG also distributes an annual assessment of climate change implications specific to each of Reclamation's geographic regions through synthesized, peer reviewed literature in coordination with NOAA RISAs and Climate Science Centers.

CCAWWG is focused on identifying the information and tools needed to improve water resources planning and management. In 2009, the founding CCAWWG agencies (Reclamation, USGS, NOAA, and USACE) collaborated to write and publish Climate Change and Water Resources Management: A Federal Perspective, USGS Circular 1331, to explore strategies to track, anticipate, and respond to climate change in water resources management. In November 2010, a CCAWWG workshop helped characterize the strengths, limitations, variability, and uncertainties that inform water resource adaptation and planning decisions by assessing a portfolio of approaches for producing climate change information. Then, in January 2011, the USACE and Reclamation published a collaborative report entitled Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information that identifies gaps in the information and tools available to help water managers in managing climate change information to make decisions for sustainable water resources planning and management.

Secretarial Order 3289 established the WaterSMART Task Force to implement the WaterSMART Program. Through the WaterSMART Program, each bureau and office under the Department is tasked to exercise its discretion, within the scope of its mission, to carry out the purpose of the SECURE Water Act. The Task Force is responsible for working within existing relationships and developing new partnerships between Federal agencies, States, and tribes to collaborate on implementation of the WaterSMART Strategy. Through the WaterSMART Basin Studies, Reclamation is partnering with entities with water and power delivery authorities, as authorized by the SECURE Water Act, to develop mitigation and adaptation strategies to meet any water supply and demand imbalances that may exist now and in the future. For example, within the

WaterSMART Basin Study, Colorado River Basin Supply and Demand Study, Reclamation is partnering with the seven basin States (New Mexico, Arizona, Colorado, Utah, California, Nevada, and Wyoming). Similar partnerships exist for other basin studies. Other key collaborators include the National Drought Information System, State Climatologists, and the Western States Water Council and Western Governors Association.

Landscape Conservation Cooperatives (LCCs) are management-science partnerships established by Secretarial Order 3289 as the applied science component of the Department's plan for a coordinated, science-based response to climate change impacts on land, water, and wildlife resources. Reclamation's collaboration within the LCC framework is part of its WaterSMART implementation. Each LCC functions in a specific geographic area and will form a national and ultimately international network to facilitate the delivery of applied science to inform resource management decisions that address climate change and other regional scale stressors. It is anticipated that, through the LCCs, additional information will be available to inform future activities and reporting, including State reports and water plans.

Over the past year, Reclamation and the U.S. Fish and Wildlife Service have formed broad-based scoping committees for the Desert and Southern Rockies LCCs, with participation by multiple State and Federal agencies; non-governmental organizations, representing a wide variety of resource interests, tribes, and universities. Reclamation conducted numerous outreach events throughout 2010 to inform stakeholders of LCC activities and to engage them to participate. Reclamation and the U.S. Fish and Wildlife Service also attended numerous meetings across the West to engage potential partners, including the Upper Colorado River Implementation Program meeting; the national Congress of American Indians Convention; and the Middle Rio Grande Endangered Species Collaborative Program meeting, among many others. In an effort to engage tribes, Reclamation held a tribes-only outreach meeting in Albuquerque on December 13, 2010; four tribes (Hopi, Navajo, Sandia Pueblo, and Southern Ute) and representatives from several tribal organizations attended this meeting. Reclamation also held an outreach meeting specifically for water resources managers in Las Vegas on September 23, 2010, and continues to meet individually with water resource departments of the States engaged in LCCs in an effort to ensure the LCC incorporates their needs and to encourage their participation.

Under Secretarial Order 3289, Secretary Salazar expanded the scope and geographic reach of the National Climate Change and Wildlife Science Center at the National Headquarters of the USGS to establish eight regional CSCs throughout the Nation. In 2010, the U.S. Department of the Interior established CSCs at competitively selected universities to maximize collaboration with academia, Federal agencies, and non-Federal partners. CSCs enable our Nation's academic expertise to play a greater role in synthesizing existing climate change impact data and management strategies to engage the public in collaborative climate change initiatives. CSCs will deliver basic climate-change impact science to LCCs within their respective regions, including physical and biological research, ecological forecasting, and multiscale modeling. CSCs will prioritize their delivery of fundamental science, data, and decision-support activities to meet the needs of the LCCs. This includes working with the LCCs to provide climate change impact information on natural and cultural resources and to develop adaptive management and other decision-support tools for managers.

11. Adaptation Actions

Water resources in the eight major Reclamation river basins addressed within this report face stresses related to climate as well as land use, population growth, and invasive species, among many others. Planning for future water management within Reclamation includes adjusting decision with respect to our systems in response to actual or potential future climate stimuli or their effects to moderate harm or exploit beneficial opportunities. Where opportunities exist, Reclamation has begun actions meant to increase adaptive capacity or strengthen conditions favorable to adaptation. These activities span across Reclamation's mission responsibilities including extending water supplies, supporting the conservation of water, hydropower production, planning for future operations, and supporting rural water development. A description is provided herein of Reclamation activities with targets within the Department of the Interior High Priority Performance Goal for Climate. The Department of the Interior High Priority Goal for Climate includes activities of the Landscape Conservation Cooperatives and Climate Science Centers, assessing vulnerabilities to the natural and cultural resources management by the U.S. Department of the Interior, and activities to adapt to the stresses of climate change.

➢ Extending Water Supplies – Pilot Run of the Yuma Desalting Plant

The Pilot Run of the Yuma Desalting Plant achieves the administration's objectives to achieve sustainability through water conservation. Between 2010–2011, a Pilot Run operation of the plant will increase water supplies in the Lower Colorado River Basin by an estimated 29,000 acre-feet, enough to supply as many as 150,000 people for 1 year. The Pilot Run also allows the U.S. Department of Interior to continue collaboration with interested stakeholders to understand cost and performance data regarding the plant. This data can be used to evaluate the long-term use of the plant to recycle and make use of saline ground water supplies. Additional conserved water would reduce the potential for conflict during periods of reduced water supply due to drought as well as assisting in offsetting the potential impacts of climate change. For the Pilot Run, successful collaboration with environmental groups and Mexico occurred to address concerns about international aspects of the run. This success may serve as a platform for future collaboration and conflict resolution.

➢ Supporting Rural Water Development – Lewiston Clearwater Exchange Project

The Lewiston Orchards Project (LOP) is an existing system that diverts water from streams on the Nez Perce Indian Reservation that are occupied by ESA-listed steelhead. Warming climate trends have shifted the water supply from a snowpack driven system to a system dependent primarily on rainfall. Earlier runoff, lower winter stream base flows, and warmer stream temperatures are expected in the future. Minimum streamflows established in a Biological Opinion for the LOP to limit the take of the steelhead and avoid impacts to critical habitat are expected to mitigate for impacts due to climate change. The Appraisal Investigation of the Lewiston Clearwater Exchange Project is a Rural Water Supply Program study of options for removing the LOP from the watershed and developing alternative water supplies while maintaining minimum stream flows necessary for the Nez Perce Tribe to manage steelhead recovery efforts.

➢ Hydropower Production – Wide Head Range Turbine

The worst drought on record since the early 1900s, resulting in decreased lake levels at Lake Mead, and the subsequent reduction of generating capacity and increased turbine rough zone operating ranges at Hoover Dam, has prompted the design and manufacture of a new "wide head" turbine runner. The new turbine design will allow the generating units at Hoover Dam to operate more efficiently and generate power over a wider range of lake levels than existing turbines, improving regulating capability by reducing or eliminating the load ranges which produce rough zones. The base contract was awarded in April 2010, and the first turbine is scheduled for delivery in February 2012 with installation performed by Hoover Dam labor forces. The option for three additional turbines may be exercised, provided the initial turbine performs as anticipated, and these additional turbines would then be delivered and installed in FY13, FY14, and FY15.

➢ Water Conservation – WaterSMART Grants[12]

Secretarial Order 3297 established the WaterSMART Program to secure and stretch fresh water supplies for use by existing and future generations to benefit people, the economy, and the environment and to identify adaptive measures needed to address climate change and future demands. WaterSMART Grants,

[12] Reclamation has been providing west-wide competitive grants that support water conservation since 2004. Reclamation is modifying evaluation criteria for FY 2012 WaterSMART grants to provide additional consideration for those applications that directly address climate change adaptation.

which implement Section 9504 of the SECURE Water Act (Subtitle F of Title IX of Public Law 111-11, the Omnibus Public Land Management Act of 2009) and is part of the WaterSMART Program, provide cost-shared assistance on a competitive basis for the following types of projects: (1) water and energy efficiency improvements that save water, increase energy efficiency and the use of renewable energy in water management, address endangered species and other environmental issues, and facilitate transfers to new uses; (2) pilot and demonstration projects that address the technical and economic viability of treating and using brackish ground water, seawater, impaired waters, or otherwise creating new water supplies within a specific locale; (3) system optimization reviews that assess the potential for water management improvement and identify specific ways to implement those improvements; and (4) research activities designed to develop tools and information to more efficiently manage water resources in a changing climate. The WaterSMART Grant Program is one of Reclamation's conservation-related programs that contributes to the Department's Priority Goal for water conservation to enable capability to increase available water supply for agricultural, municipal, industrial, and environmental uses in the Western United States by 490,000 acre feet by the end of 2012.

➢ River Restoration – Trinity River Restoration Program (TRRP)

The TRRP is beginning an appraisal study, part of the larger Klamath Basin Study, of alternatives that would improve the current cold water transmission through Lewiston Reservoir and that might increase adaptability for future climate change stressors that may impact cold water yield to the reservoir from the drainage basin.

The Trinity River (Fishery) Restoration Program (CVP – Mid-Pacific-Northern California Area Office) depends on cold water storage in Trinity Reservoir to meet temperature requirements in the Trinity River. The Carr diversion from Trinity's afterbay, Lewiston Reservoir, delivers water to the Sacramento basin, itself dependent on cold water storage in Shasta Reservoir. Lewiston Reservoir presents several problems for temperature management, including heating dependent residence time and conjunctive use for both the Trinity and Sacramento Rivers. The cold water pool behind Trinity Dam is critical to the restoration of tribal, sport, and commercial fisheries.

The appraisal study will examine the current temperature curtains in Lewiston, potential changes to the bathymetry of the lake, potential direct ties between Trinity Powerplant and Carr Tunnel as well as the Trinity River, and potential operations changes. The purpose is to reduce heating in Lewiston, increasing the reliability of the cold water reservoir behind Trinity Dam.

➢ Water Supply Planning – Bay-Delta Conservation Plan (BDCP)

The continuing conflict between ecosystem health and water deliveries through and from the Bay-Delta has reached a critical tipping point. Environmental indicators of many types—ranging from species nearing extinction to increased contaminants and continued degradation of habitat—are at their lowest points in decades. Moreover, reliable water deliveries through the Bay-Delta are imperiled by the very same environmental degradation, by inevitable drought cycles such as the one that ended only earlier this year.

Reclamation has been working with other Federal agencies and with the State of California to plan for the future given that the current infrastructure and operational approach for managing water resources in the Bay-Delta is unsustainable. While addressing the challenges in the Bay-Delta requires action on multiple fronts, the centerpiece of any such strategy is a long-term plan for ecosystem restoration and water management in the Bay-Delta. Accordingly, this update also focuses on the Federal Government’s engagement in and perspectives on development of the Bay Delta Conservation Plan, a proposed long-term plan to address critical ecosystem and water supply issues. This plan is utilizing potential changes in climate to both determine how the system would respond without action as well as how potential future strategies would perform.

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