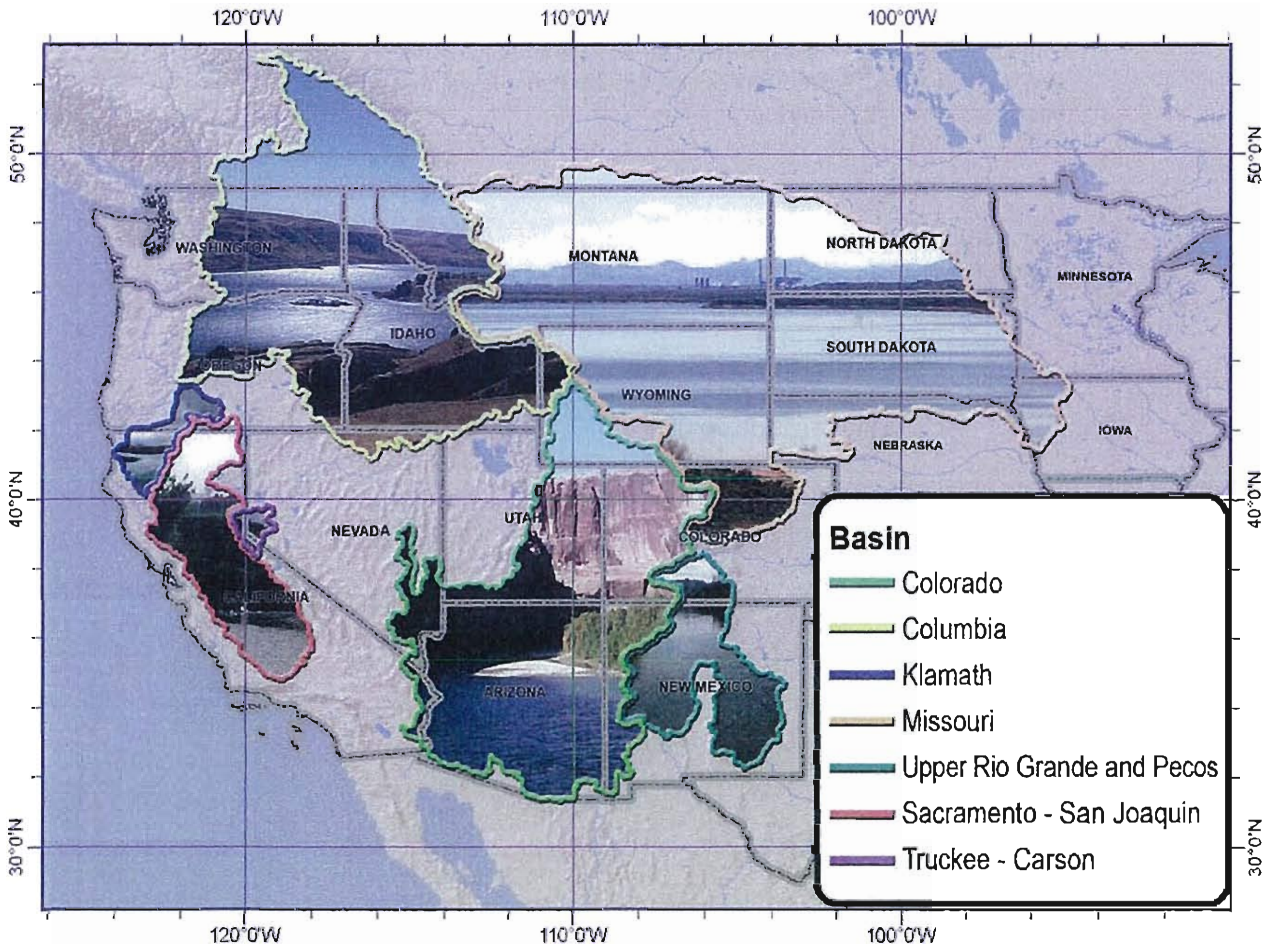
RECLAMATION

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

Prepared by:

U.S. Department of the Interior
Bureau of Reclamation

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Authors, Contributors, and Editors (in alphabetical order):

Alexander, Patty; Brekke, Levi; Davis, Gary; Gangopadhyay, Subhrendu; Grantz, Katrina; Hennig, Charles; Jerla, Carly; Llewellyn, Dagmar; Miller, Paul; Pruitt, Tom; Raff, David; Scott, Tom; Tansey, Michael; Turner, Toni

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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

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[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

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[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.

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.

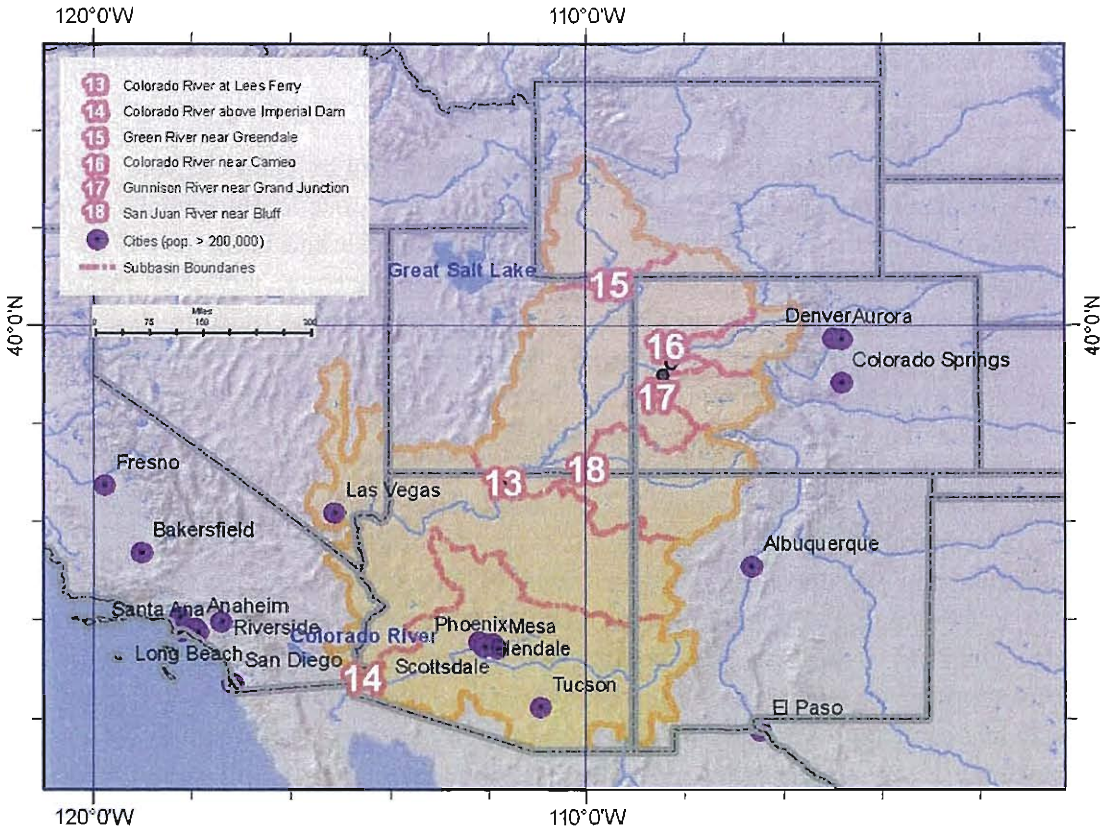

Figure 5. Colorado River Basin and runoff-reporting locations for this report.

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

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[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.

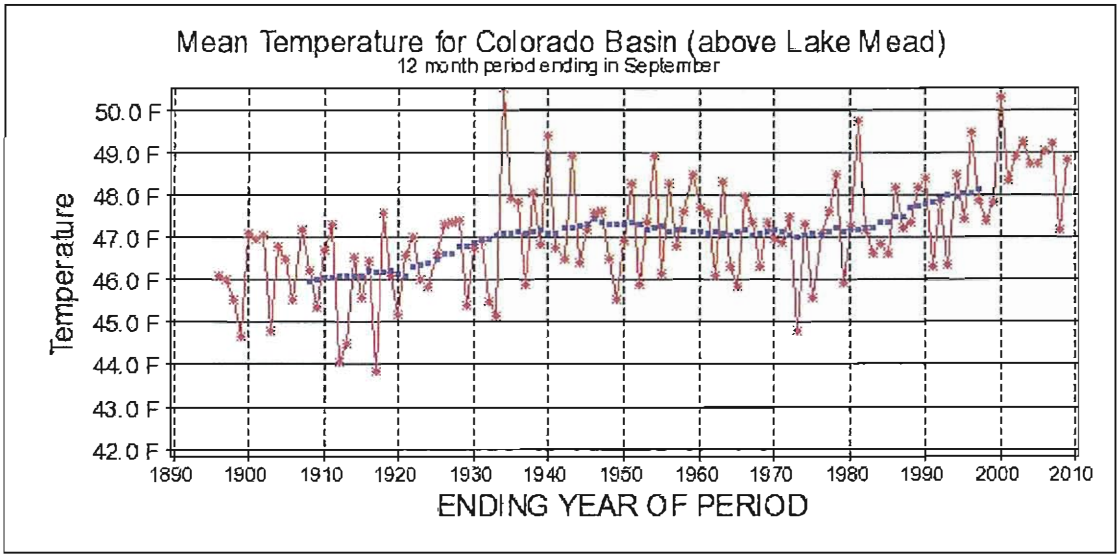
The Colorado River Basin Study contains four major phases: water supply assessment, water demand assessment, system reliability analysis, and development and evaluation of opportunities for balancing supply and demand. A scenario planning process has been undertaken to provide a framework to incorporate 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



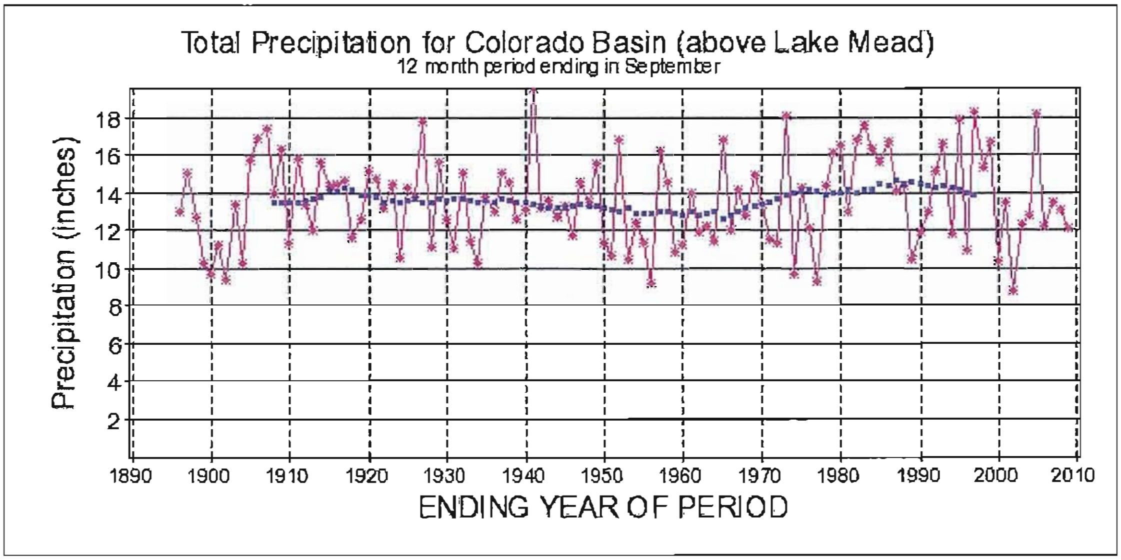


Figure 6. Observed annual (red) and moving-mean annual (blue) temperature and precipitation, averaged over the Colorado River Basin above Lake Mead.

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

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[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.

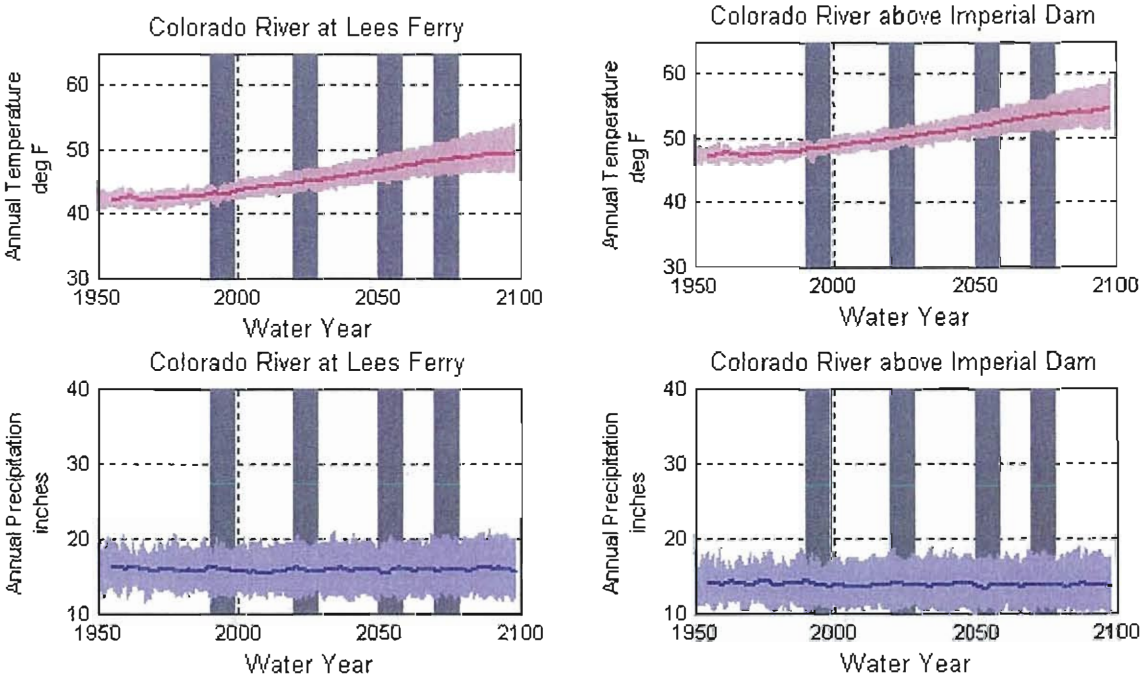

Figure 7. Simulated annual climate averaged over Colorado River subbasins.

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).

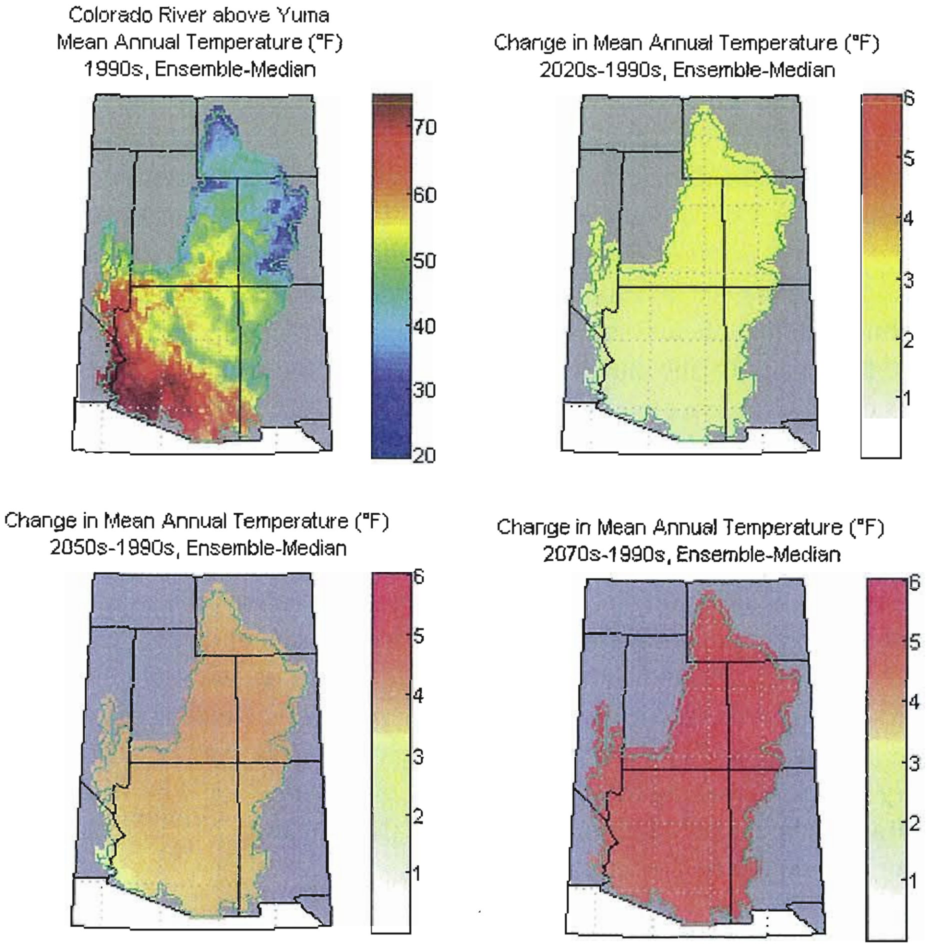

Figure 8. Simulated decade-mean temperature over the Colorado River Basin above Yuma, Arizona.

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.

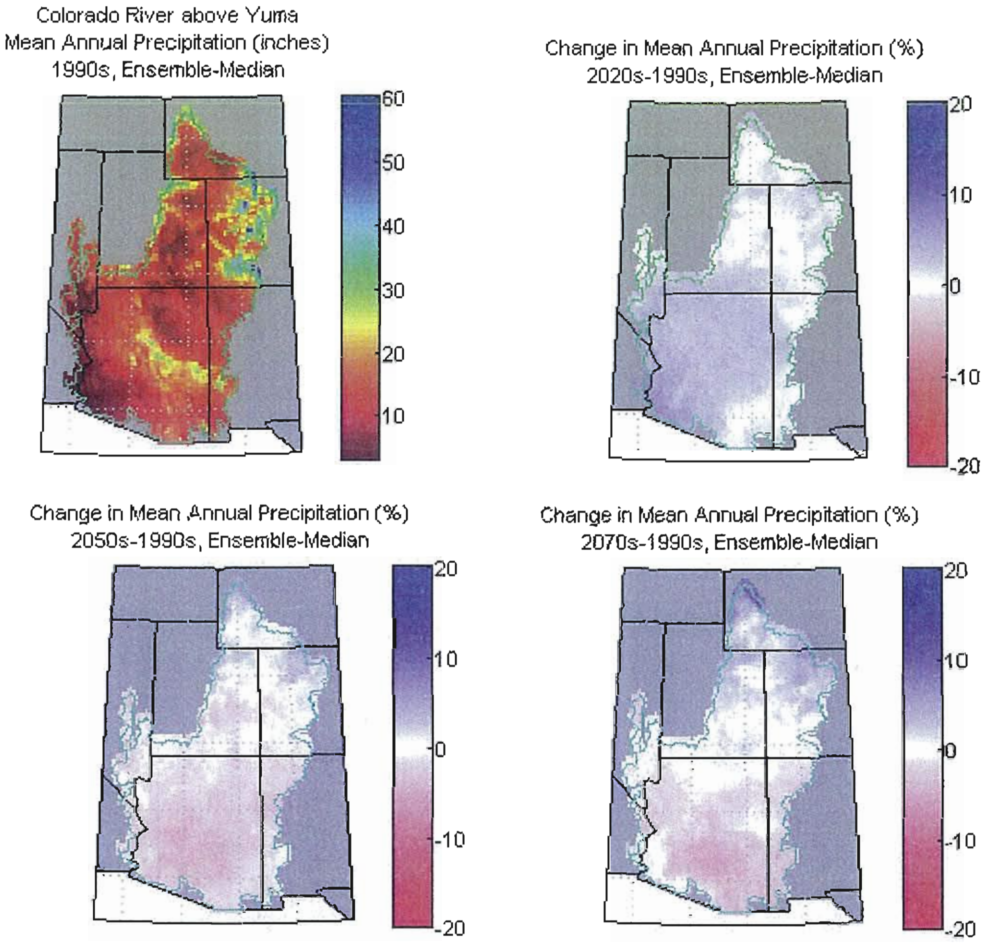

Figure 9. Simulated decade-mean precipitation over the Colorado River Basin above Yuma, Arizona.

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.

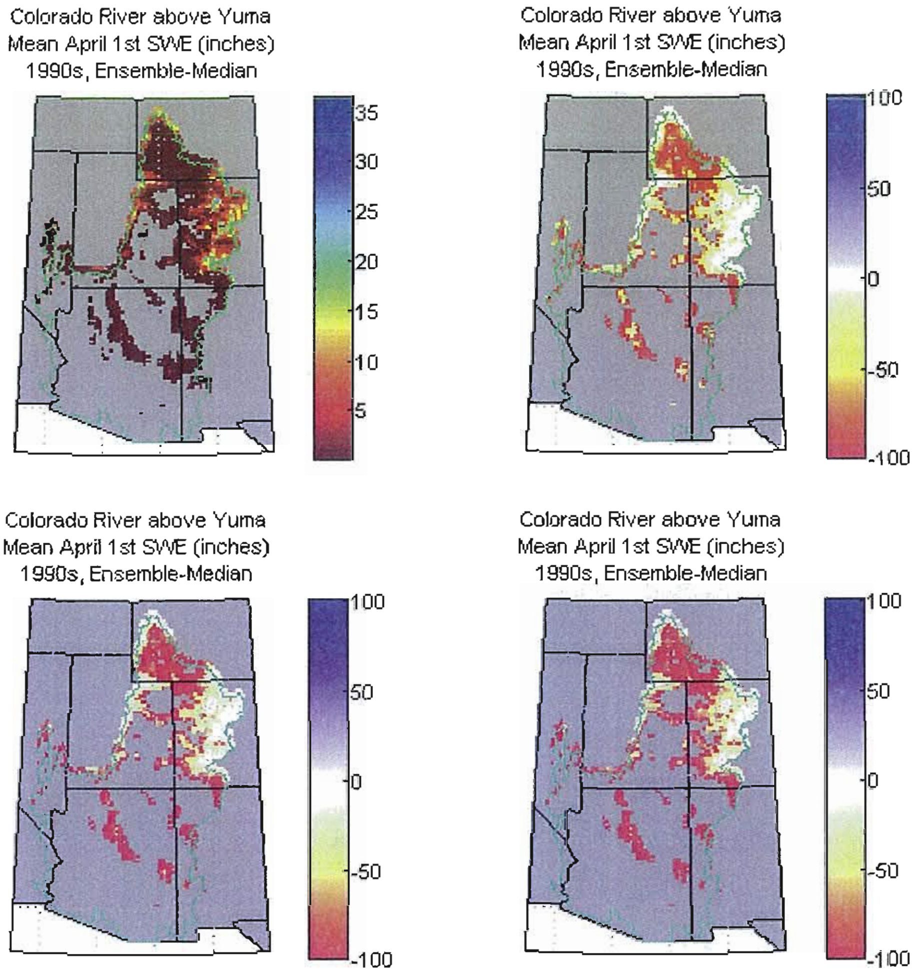

Figure 10. Simulated decade-mean April 1st snowpack over the Colorado River Basin above Yuma, Arizona.

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

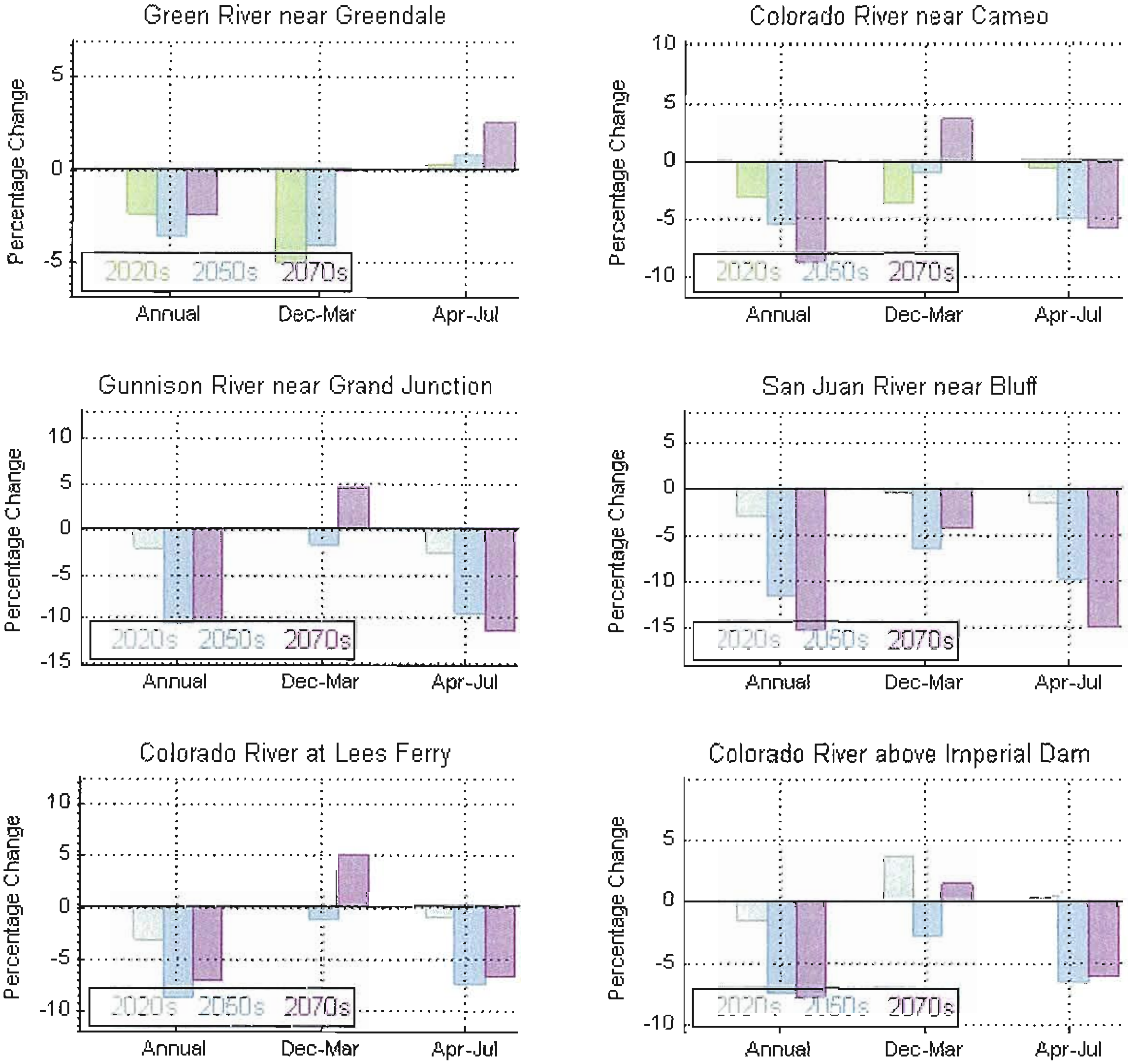

Figure 11. Simulated changes in decade-mean runoff for several subbasins in the Colorado River Basin.

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.

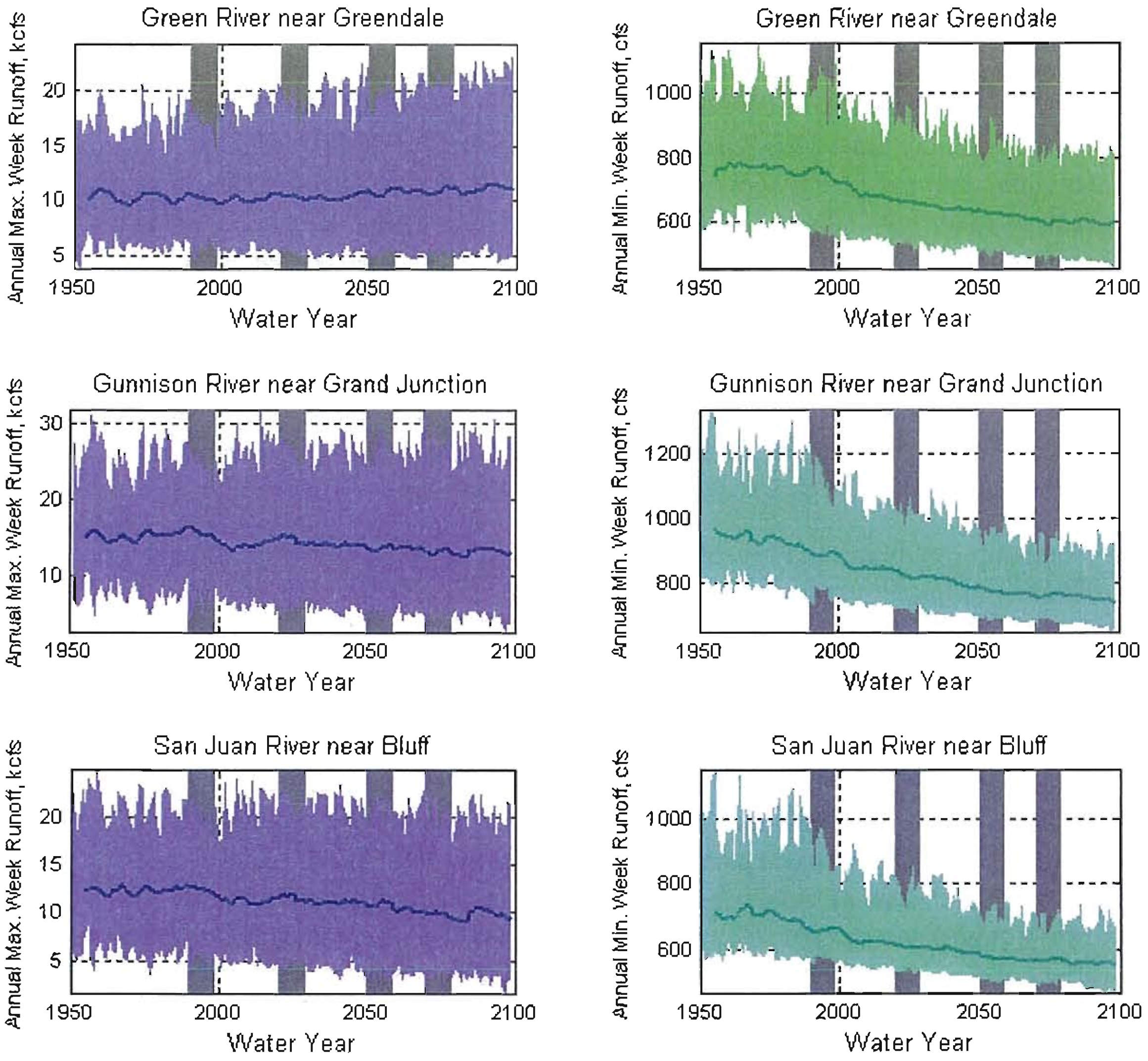

Figure 12. Simulated annual maximum and minimum week runoff for several subbasins in the Colorado River Basin.

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.