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Managing Water in the West

West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment

U.S. Department of the Interior
Bureau of Reclamation
Upper Colorado Region
Albuquerque Area Office

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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.

The U.S. Army Corps of Engineers Mission is to deliver vital public and military engineering services; partnering in peace and war to strengthen our Nation's security, energize the economy and reduce risks from disasters.

Sandia Laboratory Climate Security program works to understand and prepare the nation for the national security implications of climate change.

Participation in this study by USACE, Albuquerque District, was supported by the USACE Institute for Water Resources Response to Climate Change Program, the Middle Rio Grande Endangered Species Collaborative Program (USACE funding authority), the USACE Albuquerque District Flood Risk Management Program and the USACE Albuquerque District Reservoir Operations Branch.

West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment

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Note Regarding this West-Wide Climate Risk Assessment – Impact Assessment

The Upper Rio Grande Impact Assessment is a reconnaissance-level assessment of the potential hydrologic impacts of climate change in the Upper Rio Grande Basin. For this study, to isolate the impacts of climate change from other changes that may occur within the basin, Reclamation has assumed that current water operations by all water-management entities acting in the Upper Rio Grande Basin would continue unchanged in the future. This assessment does not consider any operational changes that may or may not be made by basin stakeholders in the future and does not reflect the position of any entity regarding future operational changes. The results should not be interpreted as an indication of actions that Reclamation or other entities may or may not take to maintain compliance with environmental laws such as the Endangered Species Act or National Environmental Policy Act, or with Interstate Water Compacts. Possible adaptation and mitigation strategies to address imbalances in future water supply and demand in the basin may be considered in a subsequent Basin Study, which would include interested stakeholders.

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Acronyms and Abbreviations

ABCWUA	Albuquerque – Bernalillo County Water Utility Authority
AF	acre-feet
AMO	Atlantic Multidecadal Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
BCSD	Bias Corrected Spatially Downscaled
BIA	Bureau of Indian Affairs
CC	Climate Change
CDF	Cumulative Density Function
cfs	cubic feet per second
CMIP3	Coupled Model Intercomparison Project 3
CO_2	Carbon Dioxide
COOP	Cooperative Observer Network
ENSO	El Niño – Southern Oscillation
EPA	Environmental Protection Agency
ESA	Endangered Species Act
ET	Evapotranspiration
GCM	Global Circulation Model
HDe	Hybrid Delta Ensemble
IPCC	Intergovernmental Panel on Climate Change
LFCC	Low Flow Conveyance Channel
LCCs	Landscape Conservation Cooperatives
M&I	municipal and industrial
msl	mean sea level
MRG	Middle Rio Grande
MRGCD	Middle Rio Grande Conservancy District
MW	megawatts
NARCCAP	North American Regional Climate Change Assessment Program
NMISC	New Mexico Interstate Stream Commission
NMOSE	New Mexico Office of the State Engineer
NOAA	National Oceanic and Atmospheric Administration
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
RCMs	Regional Climate Models
Reclamation	Bureau of Reclamation
Service	U.S. Fish and Wildlife Service
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
SWA	SECURE Water Act
SWE	Snow Water Equivalence
URG	Upper Rio Grande
URGIA	Upper Rio Grande Impacts Assessment
URGSiM	Upper Rio Grande Simulation Model
URGWOM	Upper Rio Grande Water Operation Model
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Change Research Program
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity (hydrologic model)
WaterSMART	Sustain and Manage America's Resources for Tomorrow
WCRP	World Climate Research Programme
WWCRA	West-Wide Climate Risk Assessment

Executive Summary

Background and Purpose

In the Upper Rio Grande Basin of Colorado and New Mexico, the water management challenges posed by a highly variable and extremely limited water supply have been exacerbated by prolonged drought. Water managers are asking whether the hot and dry conditions experienced in the Upper Rio Grande Basin in the past several years are related to climate change, and whether, as a result, water management planning should incorporate the possibility of a hotter, drier, and more variable future. The Bureau of Reclamation (Reclamation), with technical assistance from the U.S. Army Corps of Engineers (USACE) and Sandia National Laboratories conducted the Upper Rio Grande Impact Assessment (URGIA) as a way to begin to answer such questions.

The Upper Rio Grande Impact Assessment (URGIA) is an activity of the West-Wide Climate Risk Assessment (WWCRA), which is a component of the Reclamation WaterSMART Basin Study Program. The Basin Study Program is aimed at addressing section 9503 of the SECURE Water Act (SWA) and Secretarial Orders 3289 and 3297, supporting the U.S. Department of the Interior's coordinated response to the hydrologic implications of a changing climate. The SWA designates Reclamation to assess the risks to water supplies and demands posed by climate change, including changes in snowpack, in timing and quantity of runoff, in groundwater recharge and discharge as well as changes in demands and consumptive usage within major Reclamation river basins in the Western United States. Baseline analyses of these conditions are being performed under the WWCRA Impact Assessments and are being expanded, in cooperation with local water-management partners, through Basin Studies.

Objectives, Scope, and Uncertainty

The URGIA includes a detailed evaluation of the climate, hydrology, and water operations of the Upper Rio Grande Basin of Colorado and New Mexico, along with a quantitative evaluation of the potential impacts associated with climate change on streamflow, water demand, and water operations in this basin.

The URGIA focuses on the Upper Rio Grande Basin, defined for this study as the Rio Grande and its tributaries from the headwaters of the Rio Grande and Rio Chama in Colorado to Caballo Reservoir in south central New Mexico (locations are shown in Figure 1 in the main report). In this portion of the Rio Grande Basin, snowmelt runoff is the major contributor to streamflow.

This Impact Assessment presents an overview of the current climate and hydrology of the Upper Rio Grande, an analysis of observed trends in temperature and precipitation over the past decade, and a comparison of these trends against model projections. It also presents hydrologic projections developed from global climate models, which have been used as input to a local operations model to evaluate the ways that the projected climatic and hydrologic changes would impact water availability and management within the Upper Rio Grande. Specific risks to water supplies and demands posed by climate change, and evaluated in this study, include changes in snowpack, timing and quantity of runoff, groundwater recharge and discharge, as well as changes to evaporation, transpiration, and other water demands. These risks are then evaluated in terms of their potential impacts on key water operations and uses within the basin, as required by the SWA, including:

- Water and power infrastructure/operations
- Water delivery
- Flood control operations
- Water quality
- Fish and wildlife habitat
- Endangered Species Act (ESA) listed species and critical habitat
- Flow and water-dependent ecological resiliency
- Recreation

This Impact Assessment purposefully assesses the potential impacts of climate change alone and does not attempt to project what future development or management actions may be, including how population may change, how power generation may evolve, or how land use, including the amount and type of irrigated agriculture, may change. While factors such as these will undoubtedly be affected by climate change, they are also changing due to societal factors that are independent of climate change. It is anticipated that this information will serve as a foundation for future studies focused on developing strategies to adapt to and mitigate climate change impacts.

The projections presented here are based on reasonable assumptions about our future. Since we do not know how humans are going to behave, what energy sources they will be using, or how much carbon dioxide they will emit into the atmosphere, there is uncertainty associated with any projection of future climatic changes. Furthermore, the hydrologic projections presented in the URGIA are built upon a series of analytic steps: starting with Global Circulation Models (GCM) runs at a global scale, with downscaling and bias correction to make the results usable at a local level, followed by land surface modeling (rainfall-runoff) at a basin scale, and finally operations modeling at the river network level. Each of these steps represents a conceptual simplification of a complex physical system that is imperfectly understood. In addition, statistical methods are employed to connect the three different model types—and each statistical transformation of the output increases the uncertainties associated with the model results. Still, the projections of potential hydrologic impacts of climate change generated under the URGIA are reasonable based on the information available to date, are consistent with other projections developed for this basin, and provide a sound basis for initial conceptualization of adaptation measures.

Observed Climate Trends

To assess the current rate of temperature and precipitation change in the Upper Rio Grande and to evaluate how these rates of change compare to model projections, temperature and precipitation data from 35 climate stations in the U.S. Global Historical Climatology Network database were analyzed. Over the period 1971 through 2011, average temperatures in the Upper Rio Grande Basin rose at a rate of just under 0.7 degrees Fahrenheit (°F) per decade, a rate approximately double the global rate of temperature rise (Rahmstorf et al. 2012). Such rates of warming are unprecedented over the last 11,300 years (Marcott et al. 2013). This rate of warming has the potential to cause significant environmental harm and change the region's hydrology.

Projected Trends in Climate, Hydrology, and Water Demand

In future years, pronounced changes in climate are anticipated for the Upper Rio Grande. The climate modeling used to support this study suggests that average temperatures in the Upper Rio Grande Basin may rise by an additional 4 to 6 °F by the end of the 21st century. These model simulations do not consistently project changes in annual average precipitation in this basin, but they do project changes to the magnitude, timing, and variability of inflows to the system. Such precipitation changes, coupled with temperature-driven increases to evaporative demands within the system, are expected to cause significant changes in the available water supply and demand.

For this study, Reclamation developed projections of the hydrologic impacts of these modeled climate changes for the Upper Rio Grande Basin over the rest of this century. These projections present a picture of changing hydrology for the Upper Rio Grande, with implications for water management, human infrastructure, and ecosystems. Although there are uncertainties in the details, some general patterns are clear. The list below discusses possible implications of those general patterns.

- **Decreases in overall water availability.** Supplies of all native sources to the Rio Grande are projected to decrease on average by about one third, while flows in the tributaries that supply the imported water of the San Juan-Chama Project are projected to decrease on average by about one quarter.

- **Changes in the timing of flows.** The seasonality of flows is projected to change. Anticipated changes include earlier snowmelt runoffs as well as increased variability in the magnitude, timing, and spatial distribution of streamflow and other hydrologic variables. Projections indicate that this basin will experience a decrease in summertime flows and less of a decrease (or potentially even an increase) in wintertime flows.

- **Increases in the variability of flows.** All simulations used in this study project an increase in the month-to-month and inter-annual variability of flows over the course of the century. The frequency, intensity, and duration of both droughts and floods are projected to increase.

Water operations modeling for the Upper Rio Grande Basin using these hydrologic projections as input suggests that increasing water demands within the basin will exacerbate the gap between supply and demand. Such changes would lead to water management challenges for Reclamation and other water managers within the Upper Rio Grande Basin.

Impacts on Water Management

The decreases in supply, changes in magnitude and seasonality of flows, and increases in the availability of water supply projected in this study will present considerable challenges for water management within the Upper Rio Grande Basin. Such challenges are evaluated in this URGIA in terms of the parameters defined in the Secure Water Act (SWA), including:

- **Water Infrastructure and Operations, and Water Delivery.** The reduced surface-water inflows to the Upper Rio Grande Basin, coupled with increases in the demand for irrigated agricultural and riparian vegetation, are projected to result in decreased reservoir storage throughout the system, with commensurate impacts on water delivery.

- **Hydropower Generation.** Lower flows and lower reservoir levels associated with climate change are projected to lead to less hydropower generation. The projected decrease is substantial, from an initial generation within the Upper Rio Grande system of around 15 megawatts, the rate drops almost 50 percent to around 8 megawatts by the end of the 21st century, with most of the decrease coming during the months of May through September.

- **Flood Control Operations.** Floods are projected to become more extreme with climate change, and thus flood control operations would be needed more often in the future, even as overall supplies decrease.

- **Water Quality.** Concentrations of nitrogen, phosphorus, suspended solids, and salt may increase in the future in response to increased evaporation rates for surface water and increased precipitation intensity, which would wash a greater volume of pollutants into the river, despite a decreased overall flow volume.

- **Fish and Wildlife Habitat, Including Endangered Species Act (ESA) Listed Species and Critical Habitat.** Climate change is projected to reduce available water in the Upper Rio Grande system. This reduction in water is expected to make environmental flows in the river more difficult to maintain, and reduce the shallow groundwater available to riparian vegetation. Both of these impacts have implications for the habitat of fish and wildlife in the Upper Rio Grande Basin riparian ecosystems.

- **Flow and Water-Dependent Ecological Resiliency.** Ecological and human systems within the basin already operate close to thresholds (i.e., points at which small changes could have larger-scale repercussions) related to available water supply. It is possible that some systems in the basin have already crossed ecological thresholds. In the future, as projected water supplies decrease and demands increase, water availability thresholds may be crossed—causing additional key systems to undergo regime shifts.

- **Recreation.** The availability of water-based recreation at Reclamation and USACE reservoirs and river-based recreation, including whitewater rafting and fishing, may be negatively impacted by the projected decreases in flows. Moreover, increased temperatures may increase the usage of available water-based recreational opportunities.

- **The Rio Grande Compact.** Analyses presented in this report assume that Colorado would use its ability for priority administration to assure its obligations are met under the Rio Grande Compact. The analyses assume that New Mexico would take additional management actions to meet its obligations under the Rio Grande Compact, although in this study, Reclamation makes no assumptions about what those management actions would be. The irrigation system would be significantly impacted.

Summary of Impacts for Water Management

The projections presented in the Upper Rio Grande Impact Assessment present a picture of changing hydrology for the Upper Rio Grande, with implications for water management, human infrastructure, and ecosystems. Although there are uncertainties in the details, some general patterns are clear. This section summarizes possible implications of those general patterns.

First, our usable, manageable water supply is projected to decline. We anticipate a loss of winter snowpack, which will result in a decrease in water supply, as well as a decrease in our ability to store the water supply that we do have for use during the summer irrigation season. There will also be an increase in all outside demands (including agricultural, riparian, and urban landscaping) due solely to the projected increases in temperature. The decrease in water supply will be exacerbated by the increase in demand; the gap between supply and demand will grow even if there are no decreases in average annual precipitation.

The growing imbalance between supply and demand will likely lead to a greater reliance on non-renewable groundwater resources. Increased reliance on groundwater resources will lead to greater losses from the river into the groundwater system.

Further, the water supply to the Upper Rio Grande will be subject to increased variability and uncertainty. We are already experiencing increases in extreme temperatures. Looking ahead, we anticipate greater year-to-year variability in all aspects of our climate and hydrology.

There will also be changes in the geographic distribution and timing of runoff. Although the projections here do not portray it, other studies (e.g., Asmerom et al. 2013) have indicated some potential for strengthening of the summer monsoons, with corresponding increases in the portion of the basin’s precipitation that falls downstream of our current water storage infrastructure. The projections suggest a somewhat more reliable supply from the San Juan-Chama Project than for the native Rio Grande supply (as long as there is no across-the-board decrease in available supply in the Upper Colorado River system). A greater reliability of the imported water supply than the native supply, which has the most senior users, could have significant socio-economic implications.

Feedbacks can lead to cascading impacts. For example, more intense droughts and higher temperatures lead to a greater moisture deficit in the region’s forests. Trees that aren’t getting enough water are more susceptible to beetle infestations, and infected weakened and dead trees are more susceptible to catastrophic wildfires. Thunderstorms tend to build over fire scars because heat builds up over the blackened ground, and intense thunderstorms on the fire scars lead to the washing of ash into rivers, and to debris flows. Ash in the rivers can lead to decreased oxygen in the water and cause fish kills. Debris flows can lead to sediment accumulation in our reservoirs, and sediment accumulation in our reservoirs can lead to less flood protection for downstream human infrastructure, and so on.

And finally, all of the changes in our water supply that are projected to result from climate change would be compounded by the numerous other changes we have made to our landscape and our water supply and distribution. The analysis presented in this report attempts to project the impacts of climate change only on the water supply and demand within the Upper Rio Grande Basin, rather than predict what the future would look like in this basin. The future will depend on numerous societal choices.

Next Steps

The projections and analysis presented in this report represent a solid first step in the assessment of potential impacts in the Upper Rio Grande Basin, based on the best science and tools available at the time of initiation of the study. However, methods and tools for projecting the impacts of climate change are constantly being developed and refined. Efforts are currently underway to perform operational modeling of climate projections for the Upper Rio Grande Basin on a daily timestep for information on the ways that the projected impacts would be experienced by humans, fish, and wildlife. We also hope to perform further analyses using more recently developed simulations with models with finer resolutions.

Some WaterSMART Basin Study Program activities are available for stakeholders to pursue next steps, including:

- **Basin studies** to conduct in-depth water supply, demand, and operations analyses that are cost-shared with stakeholders and selected through a competitive process.

- **Landscape Conservation Cooperatives** to partner with other governmental and nongovernmental entities to identify, build capacity for, and implement shared applied science activities to support resource management at the landscape scale.

Reclamation is adding new activities to the Basin Studies Program that will provide stakeholders more opportunities to further refine adaptation strategies developed in Basin Studies.

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1. Study Introduction

1.1 Background and Purpose

In the Upper Rio Grande Basin of Colorado and New Mexico, the water management challenges posed by a highly variable and extremely limited water supply have been exacerbated by prolonged drought. Water managers are asking whether the hot and dry conditions experienced in the Upper Rio Grande Basin in the past several years are related to climate change, and whether, as a result, water management planning should incorporate the possibility of a hotter, drier, and more variable future. The Bureau of Reclamation (Reclamation), with technical assistance from the U.S. Army Corps of Engineers (USACE) and Sandia National Laboratories conducted the Upper Rio Grande Impact Assessment (URGIA) as a way to begin to answer such questions.

The evaluation of current trends included in this study documents temperature trends in the Upper Rio Grande Basin over the past 4 decades (the most recent decade in comparison to the previous 30-year climatic averaging period). This analysis shows average temperatures in the basin increasing by just under 0.7 degrees Fahrenheit (°F) per decade, for a total average warming since 1971 of over 2.5 °F. The climate modeling used to develop the hydrologic projections presented in this study suggests that temperatures in the Upper Rio Grande Basin may rise by an additional four to six °F by the end of the 21st century. These model simulations do not consistently project changes in precipitation in this basin, but the projected increases in temperature alone could significantly decrease the available water in the basin, due to increases in evaporation and water use by plants (transpiration).

Reclamation has developed projections of the hydrologic impacts of climate change for the Upper Rio Grande Basin over the next century, based on modeled climate projections. These hydrologic projections indicate that the basin will experience changes in the timing of flows, increases in the variability of flows, and decreases in overall water availability. Supplies of all native sources to the Rio Grande are projected to decrease on average by about one third, while flows in the tributaries that supply the imported water of the San Juan-Chama Project are projected to decrease on average by about one quarter. In all cases, the projections show an increase in variability of both monthly and annual flows over the course of the century. The seasonality of flows is also projected to change in the Colorado headwaters, the Chama and Jemez basins, and the San Juan-Chama Project tributaries.

Water operations modeling for the Upper Rio Grande Basin using these hydrologic projections as input suggests that increasing water demands within the basin would exacerbate the gap between supply and demand. Such changes would lead to water management challenges for Reclamation and other water managers within the Upper Rio Grande.

Results from the URGIA will provide important information to the water management community in the Upper Rio Grande Basin of the scale of the challenges that climate change is likely to pose in this basin and will stimulate dialogue among stakeholders to support general planning of adaptation actions. Information from the URGIA will also support Reclamation's efforts to incorporate climate-change projection into its planning for infrastructure improvements or modifications of aging infrastructure in ways that result in long-term resilience—rather than short-term fixes that can ultimately be counter-productive to climate adaptation. Thus, this information will benefit stakeholders who rely on Reclamation infrastructure. Study results can also be used to support comprehensive drought resilience planning with Reclamations stakeholders, as well as environmental compliance efforts under the National Environmental Policy Act and the Endangered Species Act.

This work is intended to be a first step in a continuing process to characterize the future climate and hydrology in the Upper Rio Grande Basin, which we anticipate will be refined many times over the years, as tools are improved and more information becomes available. Although considerable uncertainty remains regarding the future hydrology of the basin, the URGIA provides a reasonable foundation for State, regional, Tribal and local entities to partner with the Federal government to begin the process of developing strategies for adapting to and mitigating the hydrologic impacts of climate change with the basin.

1.2 Objectives and Scope

The URGIA includes a detailed evaluation of the past and potential future climate, hydrology, and water operations of the Upper Rio Grande Basin, one of the major Reclamation river basins identified for such evaluation in the SWA. The URGIA presents a quantitative evaluation of the potential impacts associated with climate change on streamflow, water demand, and water operations in this basin. As required by the SWA, specific risks to water supplies and demands posed by climate change are evaluated in this study, including changes in: snowpack, timing and quantity of runoff, and groundwater recharge and discharge, as well as changes to evaporation, transpiration, and other water demands. These risks are then evaluated in terms of their potential impacts on key water operations, conditions, and uses within the basin that are related to Reclamation’s activities, including:

- Water and power infrastructure/operations
- Water delivery
- Flood control operations
- Water quality
- Fish and wildlife habitat
- Endangered Species Act (ESA) listed species and critical habitat
- Flow and water-dependent ecological resiliency
- Recreation

This information is intended to serve as a foundation for future studies, jointly conducted by Reclamation and local water-management partners, and focused on adaptation and mitigation strategies.

The URGIA focuses on the Upper Rio Grande Basin, defined for purposes of this study as the Rio Grande and its tributaries from the headwaters in Colorado to Caballo Reservoir in south central New Mexico (see Section 2.1). In this portion of the Rio Grande Basin, snowmelt runoff is the major contributor to streamflow. The URGIA relies on climatic, hydrologic, and water -operations modeling to develop projections of the potential hydrologic impacts of climate change in this basin and assess the impacts to streamflow, water availability, reservoir operations, and water demands for irrigated agriculture and other uses.

In the URGIA, we:

- Present an overview of the current climate and hydrology of the Upper Rio Grande.

- Analyze observed trends in temperature and precipitation over the past decade.

- Compare these trends against model projections.

- Develop climate projections for the Upper Rio Grande Basin from global climate models referred to as General Circulation Models (GCMs).

- Bias-correct and spatially downscale the climate projections and use the resulting local climate projections as input to a hydrologic model, which develops hydrologic projections associated with the climate projections.

- Bias correct the hydrologic projections, and use them as input to a local operations model to evaluate the ways that the projected climatic and hydrologic changes would impact water availability and management within the Upper Rio Grande under current development conditions.

The URGIA assesses the potential impacts of climate change alone and does not attempt to project what future development or management actions may be, including how population may change, how power generation may evolve, or how land use (including the amount and type of irrigated agriculture) may change. While factors such as these will undoubtedly be affected by climate change, they are also changing due to societal factors and management actions that are independent of climate change. Reclamation does not presume to know what management actions will be taken by other entities operating in the Upper Rio Grande Basin. For these reasons, the projections presented in the URGIA should be considered as projections of the hydrologic impacts of climate change and not predictions of the future in the Upper Rio Grande Basin.

Reclamation hopes to collaborate with local water-management partners in one or more Basin Studies to evaluate the projected changes in light of potential future development and management changes. Under Basin Studies, which are awarded in a competitive process and initiated by local partners, the study teams typically incorporate management and development scenarios into the planning process for adaptation and mitigation activities that address the projected impacts of climate change and build resilience in social and ecological systems.

1.3 Document Organization

This report begins with a discussion of the purpose, basis, and authorizations for this Impact Assessment. Next it provides a description of the basin, which provides the context for the study, followed by analysis methods, and then study results. The following list breaks down which information is presented in each chapter of this report.

- Chapter 1 introduces the URGIA and describes the motivations for this work, the objectives and scope, and the programs supporting the study.

- Chapter 2 provides context for the study, presenting the historical climate and hydrology of the basin.

- Chapter 3 presents the methods used for the analysis of current trends in climate and hydrology in the basin as well as the use of climate, hydrologic, and operations models to develop projections of what the climate and hydrology are likely to look like over the next century.

- Chapter 4 describes impacts to climate, hydrology, and water supply and demand.

- Chapter 5 describes impacts to water management, including: water and power infrastructure/operations, water delivery, flood control operations, water quality, fish and wildlife habitat, critical habitat for species listed under the Federal ESA, flow and water-dependent ecological resiliency, and water-related recreation.

- Chapter 6 summarizes these impacts and provides a description of the next steps for Reclamation in its efforts to characterize the hydrologic impacts of climate change, as well as ways that local water-management entities might get involved in this effort. Technical details of the system and its operation, the modeling efforts undertaken and tools used to develop the hydrologic projections presented here.

- Appendices A through E present technical details of the system and its operation, the modeling efforts undertaken and tools used to develop the hydrologic projections presented here, and the modeling results.

1.4 Reclamation Programs Supporting this Study

Water issues and challenges are increasing across the Nation. Such concerns motivated Congress to pass the SECURE Water Act ([SWA]; Subtitle F of P.L. 111-11,) in 2009. The SWA authorizes Reclamation to implement a program to assess the risks and impacts of climate change across major Reclamation river basins in the Western United States.

A key component of Reclamation’s implementation of the SWA is the Basin Studies Program. Reclamation’s Basin Study Program is managed under the Department of Interior’s WaterSMART (Sustain and Manage America’s Resources for Tomorrow) Program, which is working to achieve a sustainable water strategy to meet the Nation’s water needs now and for the future. To learn more about WaterSMART, please visit <http://www.usbr.gov/WaterSMART/>.

The URGIA is an activity of the West Wide Climate Risk Assessment (WWCRA), which is a component of Reclamation’s Basin Study Program. The WWCRA represents Reclamation’s reconnaissance-level assessment of the hydrologic impacts of climate change, including risks to water supplies and demands. The WWCRA includes three separate activities:

1) Consistent, west-wide assessment of climate-change impacts to water supplies

2) Consistent, west-wide assessment of climate-change impacts to water demands

3) Impact assessments for individual basins or sub-basins

Individual basin Impact Assessments, such as the URGIA, address the potential risks of climate change to Reclamation facilities and operations, including water and power delivery, recreation, flood control, and ecological resources. These Impact Assessments are conducted to provide:

- A baseline analysis of climate change impacts that can be used to support future Basin Studies, in cooperation with local partners, in which impacts to multiple water uses are evaluated, and potential adaptation and mitigation strategies are developed and assessed.

- A more in-depth analysis of climate-change impacts as they relate to Reclamation facilities and operations.

Because the WWCRA Impact Assessments emphasize impacts to Reclamation facilities and operations, and because they are not focused on the development of adaptation strategies, they are conducted by Reclamation alone and are not cost-shared with non-Federal partners. This allows Reclamation to develop consistent baseline information in a time frame consistent with the reporting requirements of SWA 9503(c). Results from all three WWCRA activities contribute to Reclamations SECURE Reports to Congress every five years.

1.5 U.S. Army Corps of Engineers Programs Supporting this Study

The USACE has primary responsibility for flood control on the Upper Rio Grande under the 1948 Flood Control Act. In addition, USACE also has ecosystem restoration and recreation responsibilities in the Upper Rio Grande and plays an important role in regional water operations. Climate change is likely to impact all USACE business lines in the region directly and indirectly through hydrologic changes.

Under Executive Order 13514, USACE and other Federal agencies are required to evaluate the risk and vulnerabilities to climate change on all projects and mission areas over both the short and long term. This is also stipulated in USACE policy (Darcy 2010). USACE is specifically authorized to collaborate in the management of freshwater resources in response to a changing climate under the Interagency

Climate Change Adaptation Task Force *National Action Plan* (Interagency Climate Change Adaptation Task Force, 2011). USACE, Albuquerque District's participation constitutes an important step in fulfilling this guidance at the District level. Information gained in this study will enable USACE to better assist local, Tribal, and State governments to adapt to a changing climate its impacts on streamflow, habitats, and flood risk management on the Rio Grande and its tributaries.

Participation in this study by USACE, Albuquerque District, is supported by the USACE Institute for Water Resources Response to Climate Change Program, the Middle Rio Grande Endangered Species Collaborative Program (USACE funding authority), the USACE Albuquerque District Flood Risk Management Program and the USACE Albuquerque District Reservoir Operations Branch.

2. Location and Background

2.1 Basin Description

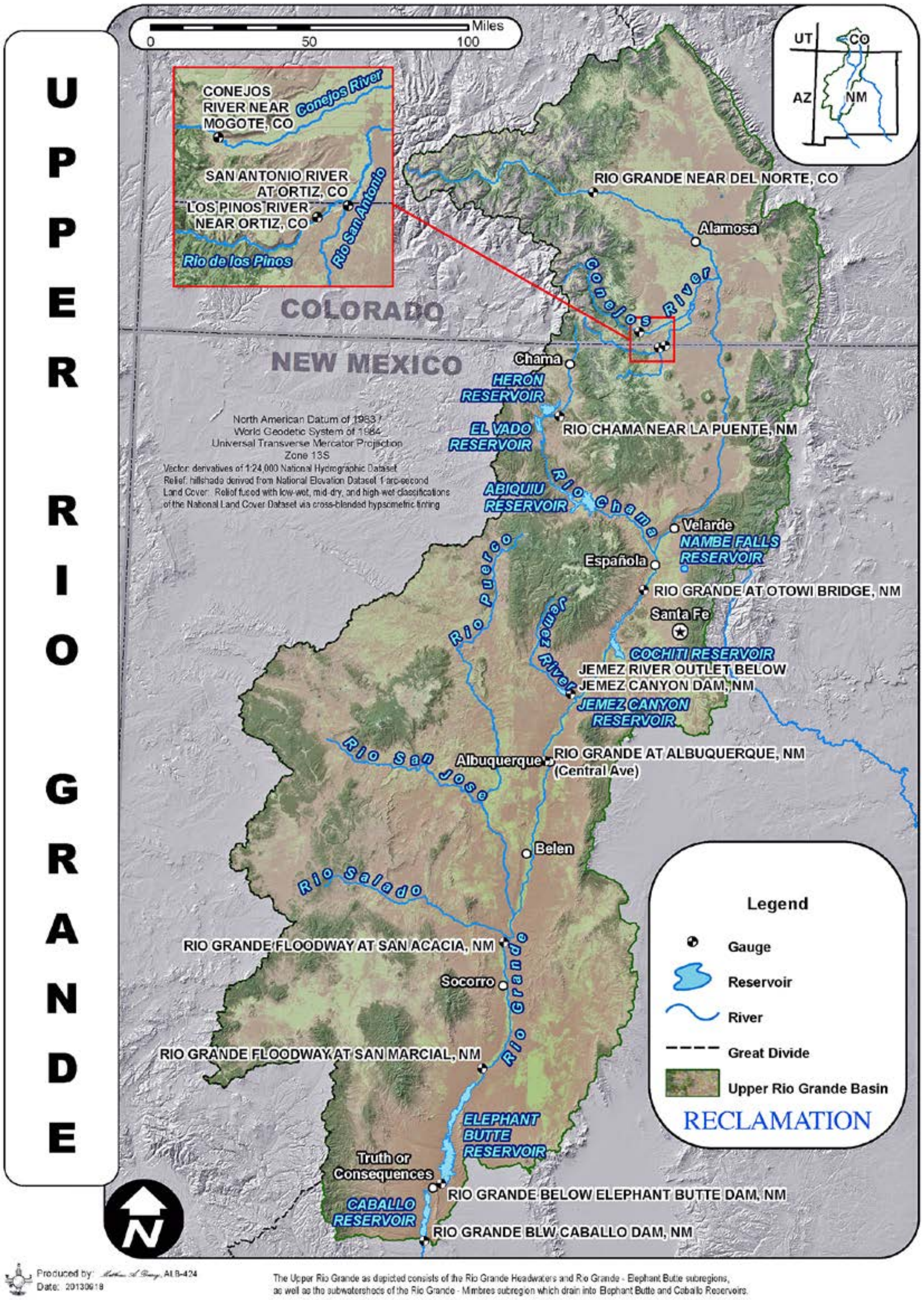
The Rio Grande Basin is located in the Southwestern United States, and runs through a semi-arid region along the western edge of the Great Plains (Figure 1).

From its headwaters in the San Juan Mountains of Southern Colorado, the Rio Grande 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. For this analysis, the “Upper Rio Grande” Basin encompasses the headwaters of the Rio Grande in Colorado to the Caballo Reservoir in south central New Mexico.

The Rio Grande is one of the longest rivers in the United States, with a total river length of 1,896 miles (3,051 kilometers [km]) and a drainage area of approximately 182,200 square miles (472,000 km^2). Basin topography varies from the mountains and gorges of the headwaters to the bosque (riparian forest) and high desert of central New Mexico, to deserts and subtropical terrain along the boundary between Texas and Mexico. The Rio Grande serves as the primary source of water for agriculture throughout the Rio Grande Valley, as well as for municipal use by the major municipalities along the river corridor (including the cities of Albuquerque and Las Cruces, New Mexico; El Paso, Texas; and Cuidad Juarez, Mexico), and environmental and recreational uses in the states of Colorado, New Mexico, and Texas, as well as in Mexico. Appendix A presents a summary of the Upper Rio Grande system, water operations and uses, and infrastructure.

Topographic diversity is a key factor as this region encompasses the headwaters of the Rio Grande in the San Juan and Sangre de Cristo Mountains of Colorado, both with peaks exceeding 14,000 feet above mean seal level; the Tusas and Jemez Mountains of New Mexico, with peaks rising above 11,000 feet above mean sea level; the Rio Grande Rift extending from the San Luis Valley of southern Colorado past the southern boundary of the study area at Caballo Dam at just over 4,000 feet above mean sea level; and areas to the west and east of the central valley that are nonetheless part of the drainage basin.

The river also supports unique fisheries and riparian ecosystems along much of its length. The basin is home to one of the largest remaining stretches of riparian cottonwood forest in the Western United States (the bosque of Central



North American Datum of 1983 /
World Geodetic System of 1984
Universal Transverse Mercator Projection
Zone 13S
Vector: derivatives of 1:24,000 National Hydrographic Dataset
Relief: hillshade derived from National Elevation Dataset 1 arc-second
Land Cover: Relief fused with low-wet, mid-dry, and high-wet classifications of the National Land Cover Dataset via cross-blended hypsometric tinting

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The Upper Rio Grande as depicted consists of the Rio Grande Headwaters and Rio Grande - Elephant Butte subregions, as well as the subwatersheds of the Rio Grande - Mimbres subregion which drain into Elephant Butte and Caballo Reservoirs.

Figure 1.—Map of Upper Rio Grande Basin with all features.

New Mexico) and includes critical habitat for the federally-endangered Southwestern Willow Flycatcher (*Empidonax traillii extimus*) and Rio Grande silvery minnow (*Hybognathus amarus*).

2.2 Surface-Water Flows

Inflows from two primary native sources and one imported source of water join to form the Upper Rio Grande. The inflows originate primarily from snowmelt runoff, local precipitation from summer monsoons, direct groundwater inflow, and return flows of groundwater from municipalities. These sources combine to provide a limited and highly variable supply of water to the region.

2.2.1 Native Inflow

The native sources of inflow to the Upper Rio Grande Basin have, for purposes of this study, been divided into the following categories:

- **Colorado headwater inflows** to the mainstem of the Rio Grande come from the southern Rocky Mountains and the San Luis Valley of southwestern Colorado. These flows account for sixty to sixty-five percent of the native inflow to the basin.

- **The Rio Chama**, including its tributary the Ojo Caliente, and the **Rio Jemez**, formed by the confluence of the East Fork Jemez River and San Antonio Creek in New Mexico, are the two major tributaries that account for about 25 percent of the flows in the basin.

- **New Mexico minor tributary inflows.** These flows account for 10 to 15 percent of flows in the basin.

Additional flows, contributed to the Rio Grande from tributary inflows within New Mexico (the major and minor tributaries identified in this study, except the Chama) especially as a result of precipitation associated with the summer monsoon, and from groundwater, were estimated in 2000 to be approximately 180,000 acre-feet per year (S.S. Papadopulos & Associates 2000).

Surface water is measured by gauges as shown in Figure 2 and Figure 3.

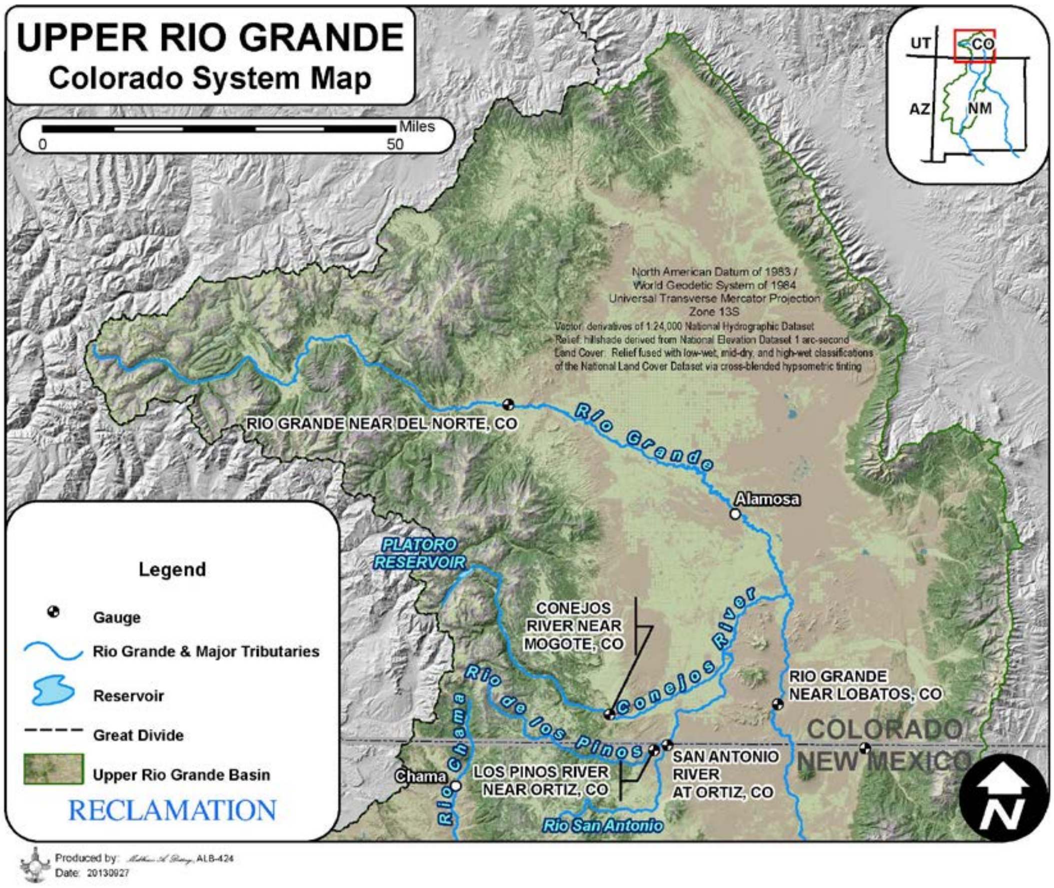


Figure 2.—Colorado gage locations.

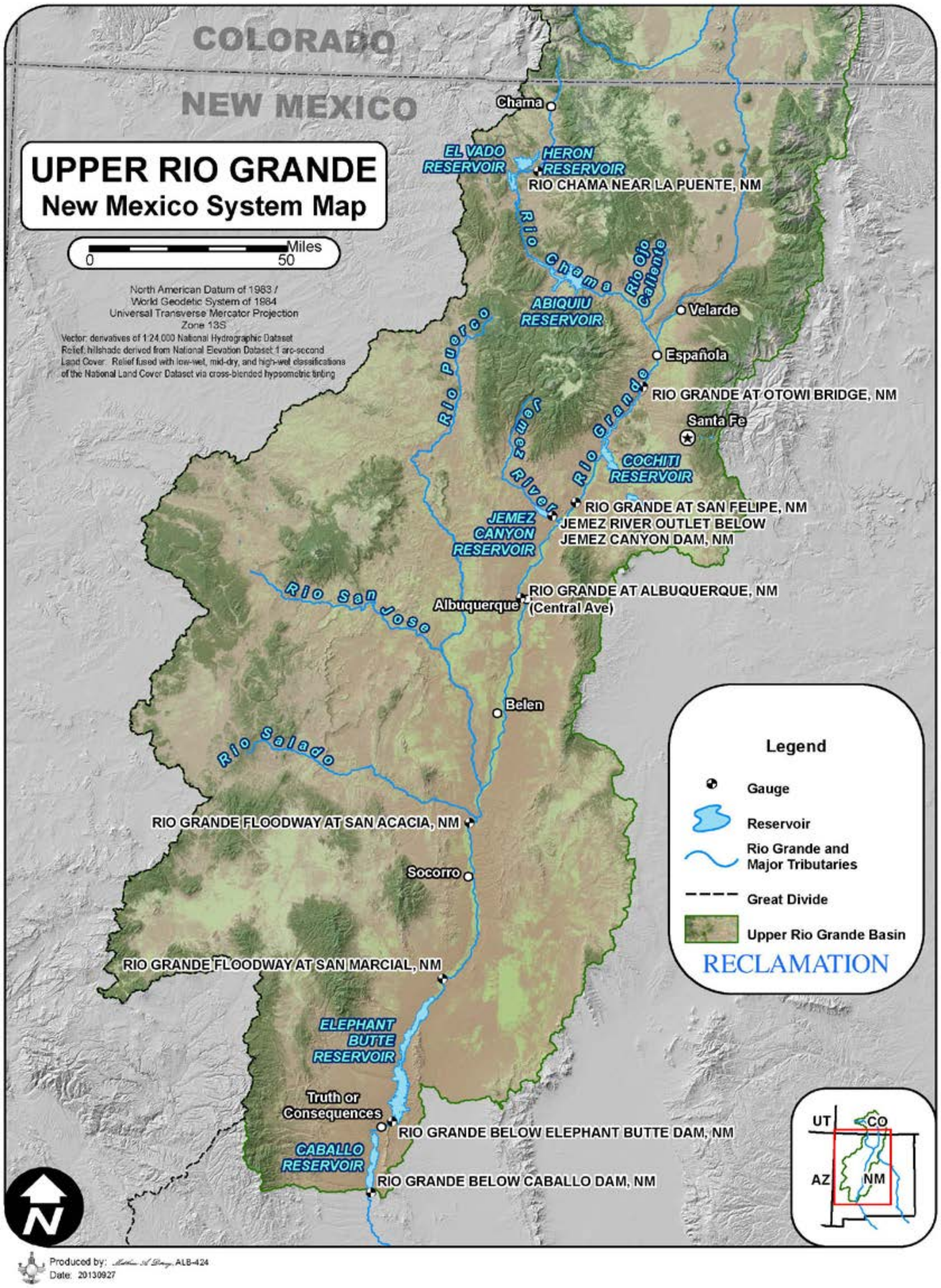


Figure 3.—New Mexico gage locations.

2.2.1.1 Imported Water

The imported water comes from Reclamation's San Juan-Chama Project, which constitutes a portion of New Mexico's allocation under the 1922 Colorado River Compact. The influx of San Juan-Chama Project water into the Rio Grande Basin was authorized by Congress in 1962 (Public Law 87-483), as an amendment to the Colorado River Storage Project Act of 1956 (Public Law 84-485) to allow diversion of a portion of New Mexico's allocation of Colorado River Basin water into the Rio Grande Basin of New Mexico.

This water flows from tributaries to the San Juan River in Colorado, and has historically provided a firm yield of 96,200 acre-feet per year. The entire amount imported from the San Juan system must be consumed upstream of Elephant Butte Reservoir, as defined under the Rio Grande Compact (Colorado et al. 1938). Reclamation maintains this water in a project pool at Heron Reservoir (Heron Dam, New Mexico), and allocates the water to contractors on January 1 of each year. The amount allocated at that time depends on the available supply in Heron Reservoir. Through 2013, Reclamation has had sufficient water in the project to provide the contractors with the full firm yield each year, although in 2013, allocation of a full supply required a secondary allocation in July. However, as the current drought continues, Reclamation may not be able to provide the full firm yield over the next several years.

2.2.2 Flow Distribution and Timing

Snowmelt processes result in streamflows from the mainstem Rio Grande, and, to a lesser degree, from the Rio Chama that peak in the late spring and early summer and diminish rapidly by mid-summer. Peak snowmelt runoff from the Rio Chama typically arrives earlier than runoff from the mainstem of the Rio Grande and is smaller in magnitude. Local precipitation primarily occurs in the summertime. Thunderstorms that characterize the region's summer monsoons feed the Rio Grande directly. These monsoons 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. While the peak runoff period typically occurs from April through June, the highest evapotranspiration and irrigation demands along the Rio Grande occur from June through mid-September.

Figure 4 depicts the average distribution in time of native flows over the last century at several gages in the Upper Rio Grande and its tributaries. This figure shows that about 60 percent of the natural runoff volume measured at the mainstem gage "Rio Grande at Otowi Bridge" (Gage # 08313000), as indicated by the Otowi Index Supply, occurs during April, May, and June and represents snowmelt runoff. Similarly, along the Rio Chama, about 80 percent of the

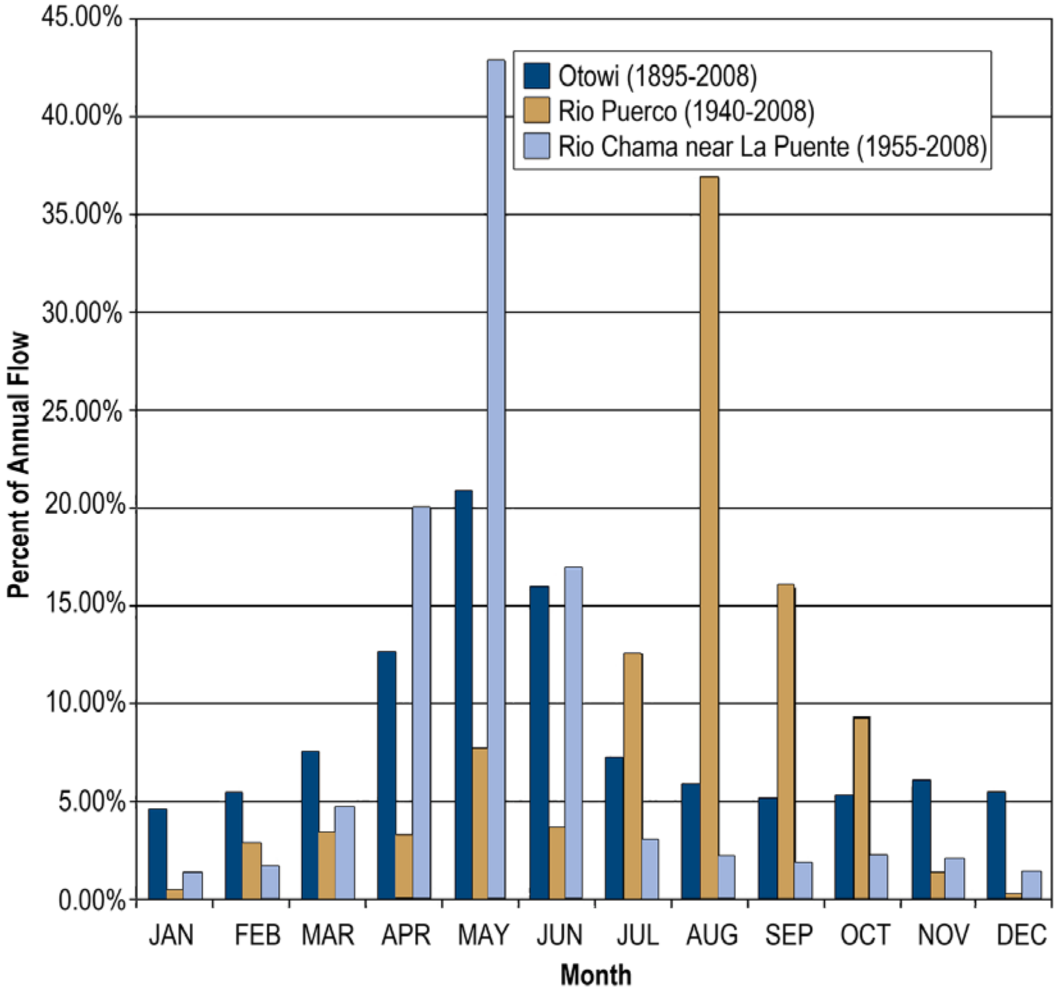


Figure 4.—Average monthly distribution of native runoff at a selection of Upper Rio Grande gages.

natural annual flow occurs during April, May, and June and is attributable to snowmelt runoff in that drainage. In contrast, the Rio Puerco, which originates in western New Mexico and primarily drains non-mountainous areas, received minimal snowmelt runoff. Nearly 80 percent of the recorded annual flow in the Rio Puerco occurs between July 1 and October 31, with nearly 40 percent occurring during August alone (USACE et al. 2007). These flows are primarily attributable to summer thunderstorms associated with the summer monsoon.

A key characteristic of the Rio Grande system is the order-of-magnitude variability of streamflow from year to year. Unregulated annual streamflow volumes at the upstream-most Rio Grande streamflow gage near Del Norte, Colorado, vary from less than 100,000 acre-feet up to well over 1,000,000 acre-feet. This high variability is evident in Figure 5, which depicts nearly five centuries of Rio Grande streamflow near Del Norte, Colorado, reconstructed from tree-ring analysis. The series of wet years from the mid-1980s through the 1990s register as one of the five wettest periods in this 500-year period.

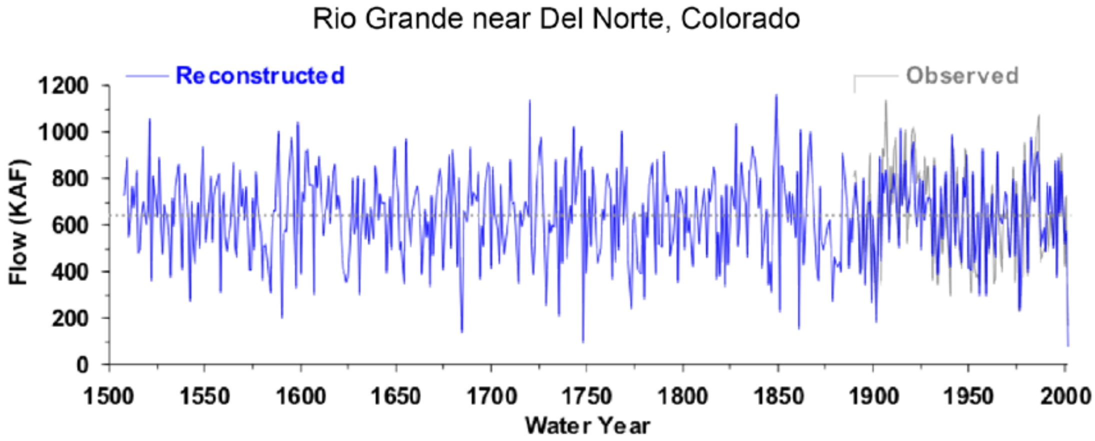


Figure 5.—Long-run (1536-1999) tree-ring reconstructed streamflow of the Rio Grande near del Norte (based on Woodhouse 2012).

Figure 6 shows a summary plot of the Otowi natural flow reconstruction distributed for annual flows in each century shows the median, 25th and 75th percentiles and the relatively extreme variability at the 5th and 95th percentiles. The plot shows that, on average, the 1900s have been slightly less variable and wetter than the previous four centuries (Lukas 2008). This suggests that annual flows measured in the 20th century may not be good indicators of the full range of historic variability.

Droughts, defined as a year or more with annual flows less than the long-term median (<1,800,000 acre-feet unregulated flow at the Otowi Gage), are common in the historical record, with several long-duration droughts lasting longer than 20 years. The 20th century record (1900 through 2000) includes only one period with a long-duration drought, which lasted 16 years. An additional long-duration drought straddled the two centuries, extending from 1996 to 2013.

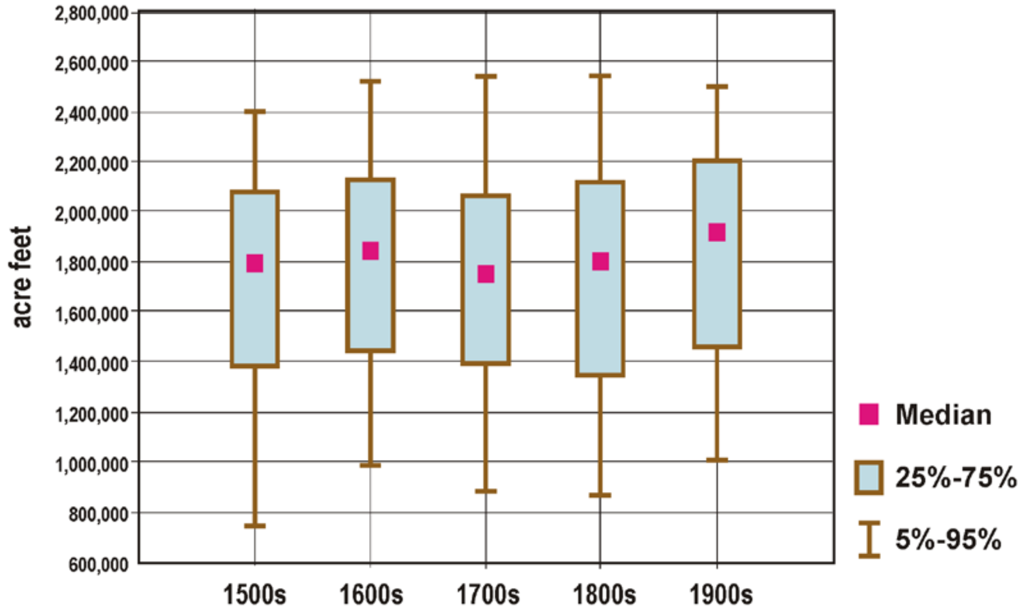


Figure 6.—A box and whisker plot of the Otowi natural flow reconstruction distributed for annual flows in each century (Lukas 2008).

2.3 Groundwater Supply

Since around 1940, groundwater development has exploded in the Upper Rio Grande Basin, primarily to support municipal and industrial development, but also to supplement irrigation and for domestic use. Groundwater use now exceeds 170,000 acre-feet per year in the Albuquerque Area and has caused ground-water level declines of up to 160 feet in some locations (McAda and Barroll 2002). Although these declines are not large relative to the thickness of the aquifer, which is several thousand feet, they represent the removal of the highest quality water, since the salinity of the aquifer increases with depth. This removal of water from the groundwater system induces flow from the river to the groundwater system, which causes decreases in river flows.

The impacts of groundwater pumping on flows in the river have historically been offset through the retirement of surface-water rights, primarily from agriculture, and through contracting of San Juan-Chama Project water, and provision of the resulting “offset” water to irrigators in the summertime and to Elephant Butte deliveries in the wintertime. However, these measures have not mitigated the considerable impact groundwater pumping has had on the continuity of river flows. In 1956, the New Mexico State Engineer estimated that the Rio Grande between the Colorado state line and the mouth of the Red River in Texas gained 93,000 acre-feet per year (Jones, 2002). But by 2002, the Middle Rio Grande alone was estimated to lose 95,000 (Brekke et al. 2009 and Jones 2002) acre-feet per year.

2.4 Basin Development History

Largely due to the limited water supply and the highly variable streamflows in the Rio Grande, humans have modified the Rio Grande system over time to protect themselves from floods and to maximize their beneficial use of water. Humans have used the flows of the Rio Grande for thousands of years. Pueblo oral histories convey, and the archaeological record shows, that Pueblo peoples had developed systems of irrigated agriculture long before the coming of Europeans. Beginning with the reestablishment (after the Pueblo revolt) of Spanish settlement in the late 17th century, expanded irrigation activities began to affect the flows in the Rio Grande system. The subsequent agricultural practices and administration of the river, as well as the intensive use of non-irrigated lands within the Rio Grande Basin, during the Spanish, Mexican, and American periods brought about changes to the shape and behavior of the river's flows through time (i.e., the hydrograph), the distribution of flows in time through that river, and the habitat of the species that depend on that river for life. The greatest of these changes, by far, have been made over the past century.

From the 1930s through the present, dam and levee construction, construction of irrigation and drain system, changing land use patterns, and river channelization, as well as ground-water pumping, has significantly altered flows in the Rio Grande and the relationship between surface water and ground water throughout the Upper Rio Grande. Operation of flood control and water storage dams alters the shape of the hydrograph, as well as the amount of water that is conveyed through the river. The alterations of the hydrograph have allowed the maintenance of a continuous riparian corridor, which was not present historically, and which is hospitable to non-native riparian species including tamarisk (salt cedar) and Russian Olive. This riparian system is encroaching on the river and causing further channel narrowing (Scurlock 1998, Lagasse 1980, and Makar et al. 2006).

Nine dams (Platoro, El Vado, Abiquiu, Nambe Falls, Cochiti, Galisteo, Jemez Canyon, Elephant Butte, and Caballo) plus three cross-river diversion structures and minor diversions between Embudo and Abiquiu reservoirs have been constructed on the Upper Rio Grande or its tributaries over the past century by the USACE, Reclamation, the Middle Rio Grande Conservancy District (MRGCD), and in cooperation with other non-Federal partners (see Figure 7 for locations of these dams). These dams and diversion structures affect the flow and sediment distribution along the river. They alter flows by storing and releasing water in a manner that generally decreases flood peaks and alters the distribution in time of the flows. The major dams also trap significant amounts of sediment, causing buildup and increases in channel elevation upstream, and riverbed degradation (lowering of the riverbed) and coarsening of riverbed sediment in the reaches below the dams.

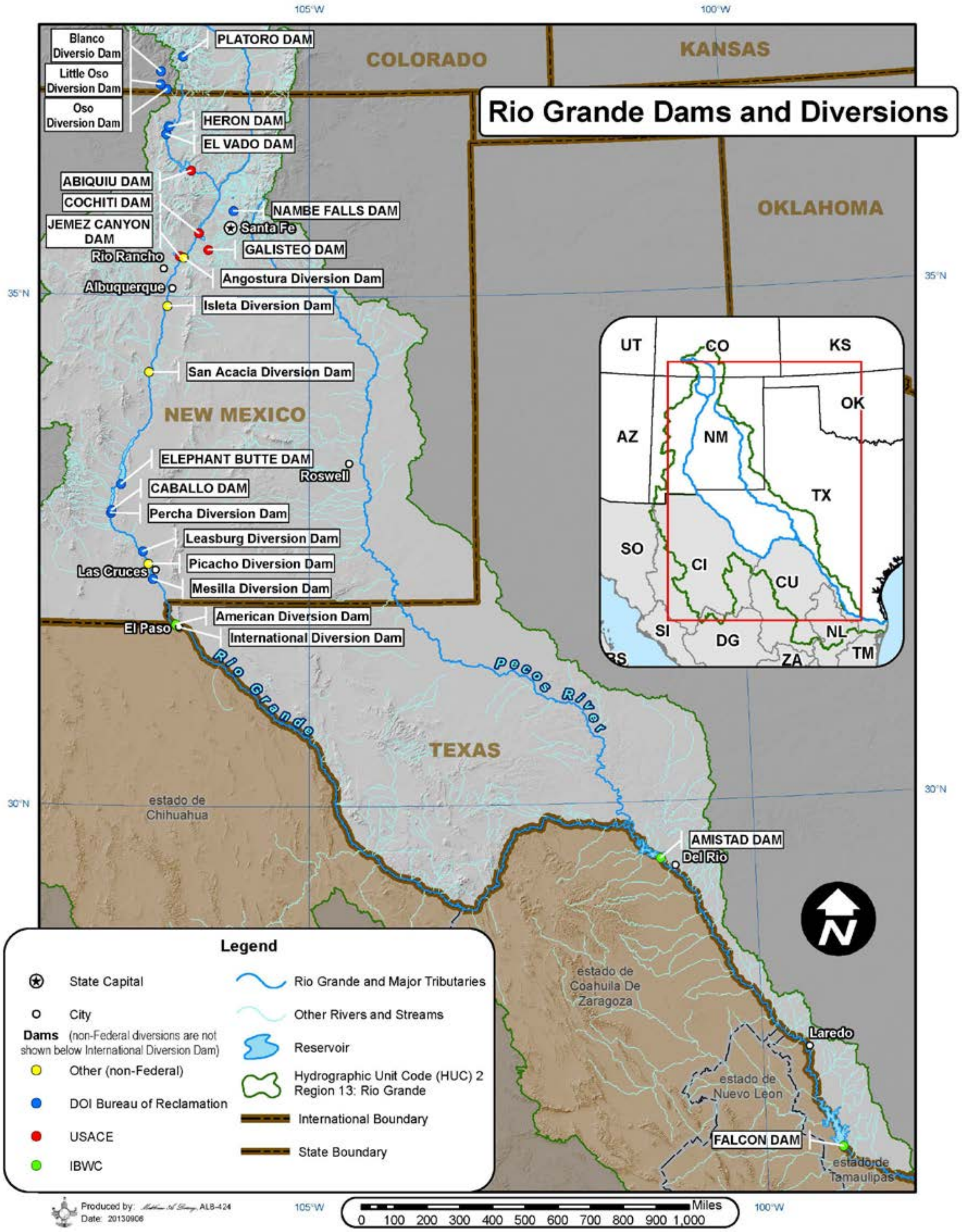


Figure 7.—Dams and diversion dams in the Upper Rio Grande Basin.

3. Assessment Approach and Sources of Uncertainty

To evaluate the ways that climate change would impact water availability and management within the Upper Rio Grande, the URGIA:

- Presents an overview of the current climate and hydrology of the Upper Rio Grande, an analysis of observed trends in temperature and precipitation over the past decade, and a comparison of these trends against model simulations for the same period.

- Compares observed trends in temperature and precipitation over the past decade with trends in temperature and precipitation from model projections.

- Develops projections of the impacts of climate change on water supply and demand through 2100, according to the procedure shown in Figure 8:

    - Downscale temperature and precipitation projections from global climate models to a spatial scale relevant for regional planning.

    - Performs hydrologic modeling to develop specific projections of streamflow within this basin.

    - Uses these streamflow projections to simulate future operations of Reclamation projects and related Federal and non-Federal activities and infrastructure in the basin with the available water supplies and anticipated demands to develop a picture of future changes in water supply and demand that can be expected as a result of climate change alone.

- Uses projections of temperature and precipitation from GCMs in combination with observed data and hydrologic projections generated from future climate projections as inputs to a local monthly operations model, the Upper Rio Grande Simulation Model (URGSiM).

Details describing the methods employed in each of these steps are provided in Appendix D. A general description of the process used to develop climate-change projections is presented in this section.

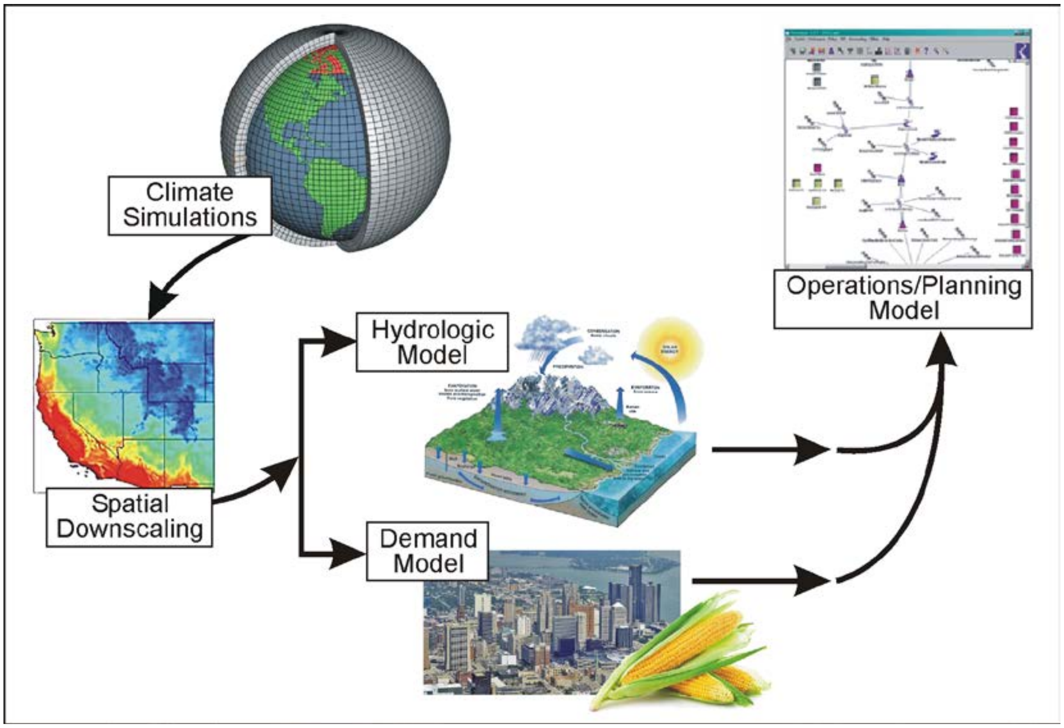


Figure 8.—Modeling and analytical steps involved in the development of local hydrologic projections.

3.1 Analysis of Recent Trends in Climate

Mountain climates are complex and vary over short distances due to aspect and relief, which influence temperature and precipitation via cold air drainage, down and up-canyon winds, variation in the duration of direct versus indirect insolation, vegetation cover, duration of snow cover, and other factors (Beniston 2006 and Barry 2008). Changes at individual stations may differ from regional climate trends (Pepin et al. 2005) in ways that are strongly influenced by landscape position, topography, and elevation (Lundquist and Cayan 2007). For example, valley floors may lag regional warming, particularly in winter months, due to the increasing frequency and severity of temperature inversions under more stable conditions (Daly et al. 2010 and Seth et al. 2011). Because of these complexities, some locations in each data set exhibited trends counter to the remainder of the sites, and these data may reflect real, but local climate differences. They may also reflect changes to station equipment, setup and location, although most of the data records have been adjusted to account for such factors.

Trend analysis was conducted using temperature and precipitation data obtained from the National Climate Data Center (NCDC) representing observations from:

- Thirteen (13) USDA Natural Resources Conservation SNOTEL (snowpack telemetry) stations with periods of record 1989-2012 for high elevation sites in the Jemez, Tusas, Sangre de Cristo, and San Juan Mountains.

- Twelve (12) National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Network (COOP) stations with periods of record covering 1971 through 2012 for low elevation agricultural and non-agricultural areas in the state.

- Eleven (11) NOAA National Weather Service Historical Climatology Network 2 (HCN) data a mix of high and low elevation areas in the state.

Stations were grouped into physiographic regions for analysis:

- Mountainous areas included the San Juan, Sangre de Cristo, Tusas, and Jemez Mountains, with sites generally at or above 7,500 feet above mean sea level (msl). Seventeen (17) sites fall into this category.

- Valley areas included the San Luis Valley, the Rio Chama and Jemez River valleys, the Middle Rio Grande below Cochiti Dam, and areas within the watershed that lie east of the Manzano and Sandia Mountains (Plains). Nineteen (19) sites fall into this category.

Statistical methods used to evaluate these trends are described in Appendix C.

3.2 General Description of Climate Change Projections

Evaluation of the long-term availability of water supplies typically involves a combination of approaches that characterize both past and projected climate and climatic variability. These approaches may include use of paleo-climatic and paleo-hydrologic indicators (e.g., tree rings, pollen, ice cores, ocean and lake sediments, stable and radioisotopes) that capture the natural climate variability over thousands of years—which may exceed the range of variability found in the instrumental record. This information is evaluated statistically to characterize the uncertainties in climatic conditions. Projections of future climate changes are usually developed through the use of GCMs, which have been steadily increasing in sophistication and complexity over the past several decades.

3.2.1 Projections and Emissions Scenarios

The World Climate Research Programme (WCRP) Coupled Model Inter-comparison Project Phase 3 (CMIP3) (Meehl et al. 2007) produced multiple climate projections for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007). These climate projections are based on an assemblage of GCM simulations of coupled atmospheric and ocean conditions, with a variety of initial conditions of global ocean-atmosphere system, and four distinct "storylines" or "scenarios" about how future demographics, technology and socioeconomic conditions might affect the emissions of greenhouse gases. These are more fully described in the IPCC Special Report on Emissions Scenarios (IPCC 2000), which states that the emission scenarios are potential futures based on assumptions of global economic activity and growth, as shown in Figure 9, Panel A. The IPCC (2007 [Summary]) explains: "They cover a wide range of key "future" characteristics such as demographic change, economic development, and technological change. For this reason, their plausibility or feasibility should not be considered solely on the basis of an extrapolation of current economic, technological, and social trends" (page 4). The four families of emission scenarios are:

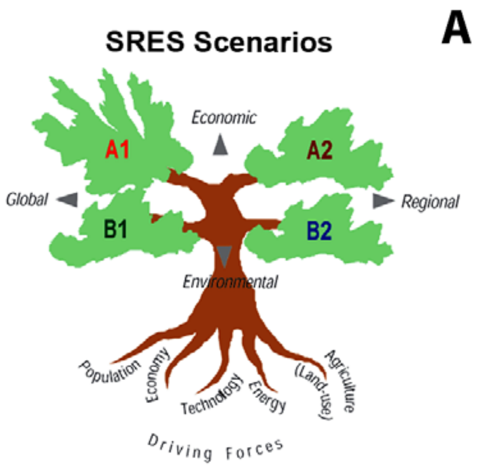
- A2 (high emissions). The A2 storyline and scenario family describes a very heterogeneous world. Economic development is primarily regionally oriented, and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

- A1B (moderate emissions). The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. A1B storyline posits a technological change that is balanced across fossil and non-fossil energy sources.

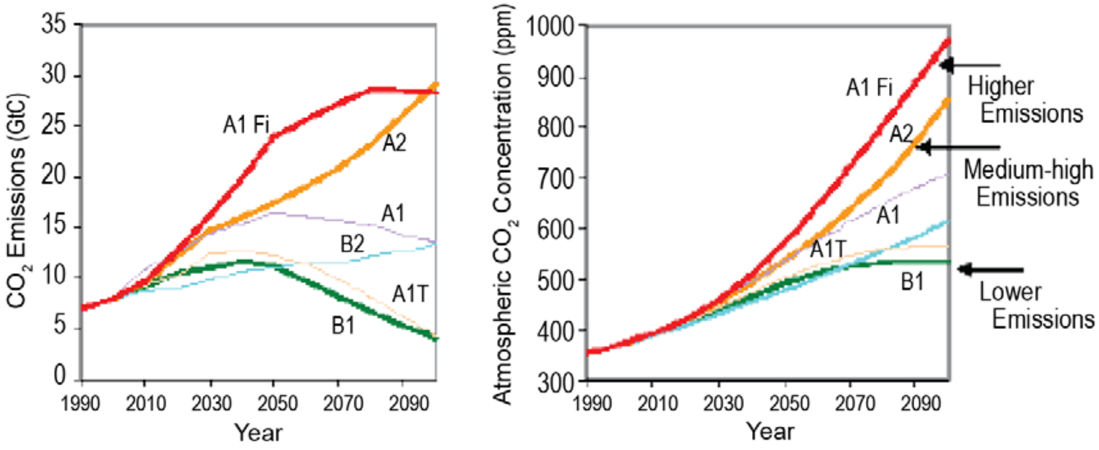
- B1 (low emissions). The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

- B2 (moderate emissions). The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

Corresponding carbon dioxide (CO_2) emissions and atmospheric concentrations for some of the emissions scenarios are shown in Figure 9, Panels B and C below.



Conceptual representation



B Time-evolution of CO$_2$ emissions

C Time-evolution of CO$_2$ concentrations

Figure 9.—Carbon dioxide emissions and atmospheric concentrations for the four families of emission scenarios used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007).

The development of climate projections by the WCRP and an associated assessment report by the IPCC is a recurring 7-year process. The next generation of climate projections, Coupled Model Inter-comparison Project Phase 5 (CMIP5) was not available at the time that the analyses were performed for the URGIA. However, these projections have recently been developed and are providing the basis for the next IPCC assessment report (Fifth Assessment Report, or AR5), which is currently being prepared. Although the most recent suite of climate projections based on the CMIP5 models use a different approach for representing future greenhouse gas emissions, and many of the GCMs have improved representations of the physical atmosphere-ocean system, projections based on CMIP3 are still widely used in Impact Assessments and remain a valid approach for evaluating climate change impacts.

The spatial resolution of the GCM climate projections is typically on the order of 1-2 degrees of latitude/longitude, which is too coarse for use in regional and project-scale planning because finer scale geographic features, which may significantly influence local climate, are not represented. Also, GCM output is generally archived on a monthly timescale, adding to the limitations of its use for water resources planning studies. Therefore, projections of finer scale regional conditions require a method of downscaling GCM projections in both space and time. Typical downscaling methods include:

- Dynamical, which uses Regional Climate Models (RCM) that are based on boundary conditions defined by GCMs.

- Statistical, which uses statistical techniques to relate finer-scale regional climate characteristics to larger scale GCM projections.

Although dynamical downscaling is increasingly used as a methodology for producing climate projections, it is computationally intensive, which makes it prohibitive for many long-term planning studies. The URGIA relies on the statistical downscaling approach for development of future climate projections.

Statistical methods have been widely applied to produce spatially-continuous fields of temperature and precipitation at fine scales (< 10 miles) covering the entire United States. Reclamation, in cooperation with Lawrence Livermore National Laboratory, Santa Clara University, Climate Central, and the Institute for Climate Change and its Societal Impacts, have developed an archive of 112 monthly and daily statistically downscaled projections of temperature and precipitation based on CMIP3, using the Bias Correction and Spatial Disaggregation (BCSD) technique of Wood et al (2002). These projections cover the entire United States at 1/8 degree spatial resolution (12 km) for the period from 1950 through 2099. These projections were produced from results of 16 different CMIP3 GCMs, simulating 3 different emissions scenarios (A2 [high emissions], A1B [moderate emissions], B1 [low emissions]) along with various assumptions about initial ocean and atmosphere conditions. A detailed description of the BCSD method is contained in Reclamation's Bias-Corrected and Spatially Downscaled Surface Water Projections report (Reclamation 2011c). An overview of the approach is provided in Appendix D.

3.2.2 Streamflow Simulations

Streamflow simulations based on projections of future climate using the BCSD approach described above were performed using the Variable Infiltration Capacity

(VIC) Model. The VIC model (Liang et al. 1994, Liang et al. 1996, and Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. It has been widely used in large-scale hydrologic studies across the globe to explore the implications of climate change on water. To produce future projections of streamflow consistent with the above described statistically downscaled climate projections, the VIC model is applied once for each set of temperature and precipitation projections associated with a GCM and emissions scenario combination (i.e., the 112 simulations in CMIP3). The VIC model generates simulated natural streamflow over the period 1950 through 2099, consistent with the time period for transient (or BCSD) climate projections.

The VIC model of natural streamflow projections is most useful if analyzed at a monthly time step, as was done for the URGIA. Daily time-steps have been found to frequently contain unrealistic daily precipitation estimates, especially at smaller spatial scales of interest in water resources planning.

Using a similar approach to that used for BCSD to remove systematic biases in GCM simulations, we applied a bias correction procedure to remove systemic biases in the VIC model of natural streamflow projections. Bias-correction techniques may be applied at locations where reconstructed observed natural streamflows exist. These techniques produce flows that very closely match the long-term statistics and time series behavior of a natural or modified flow dataset for a particular site.

We used the developed streamflow projections from the VIC model were used as input to the Upper Rio Grande Operations Model URGSiM to simulate the effects of local water operations on the projected available water. URGSiM uses hydrologic and climatic inputs (e.g., monthly flow, precipitation, and minimum and maximum temperature) to simulate the movement of surface water and ground water through the Upper Rio Grande system from the San Luis Valley in Colorado to Caballo Reservoir in southern New Mexico including the Rio Chama and Jemez River tributary systems, and the Española, Albuquerque, and Socorro regional groundwater basins. URGSiM simulates:

- Operations of nine dams
- Interbasin transfers from the Colorado River Basin to the Rio Grande Basin (via Reclamation's San Juan-Chama project)
- Agricultural diversions and depletions in the Chama, Española, and Middle Rio Grande Valleys (most of which occur via irrigation infrastructure originally built by Reclamation as part of the Middle Rio Grande Project)

- Evapotranspiration (ET) i.e., the evaporation plus water use by riparian plants and crops

3.2.3 Base Case Model Run

The operations model scenario used for most of the analyses presented in the URGIA, termed the “Base Case Scenario,” only represents changes that result directly from projected changes in the climate. Infrastructure, reservoir operations, human population, irrigated agriculture, and other non-climate-related parameters have stayed the same, to allow our analyses to isolate the impacts of climate change on river and water-management systems. These other factors will need to be considered in water-management planning for the Upper Rio Grande Basin, potentially as part of a Basin Study, but these are not considered here.

3.3 Sources of Uncertainty

The projections presented here are based on reasonable assumptions about our future. Since we do not actually know how humans are going to behave, what energy sources they will be using, or how much carbon dioxide they will emit into the atmosphere, there is uncertainty associated with any projection of future climatic changes. For example, since the initiation of work on the URGIA, carbon dioxide emissions have been high enough that it is very unlikely that we will have a future consistent with the B1 (low emissions) scenario used in the URGIA analysis. Our emission scenarios are constantly being refined, and the generation of hydrologic projections will need to be as well. The analyses presented in the URGIA are based on the CMIP3 suite of GCM simulations associated with the IPCC’s 4th Assessment Report (AR4). Since work began on the URGIA, an additional suite of GCM simulations (known as CMIP5) has become available, and Reclamation is currently working to develop hydrologic projections based on these updated model runs. However, these new projection sets were not available to support the analyses presented here. Still, the projections of potential hydrologic impacts of climate change generated under the URGIA are reasonable based on the information available to date and provide a sound basis for initial conceptualization of adaptation measures.

As discussed at the beginning of this chapter, and shown in Figure 8, this analysis is built upon a series of analytic steps: starting with GCM runs at a global scale, downscaled and bias corrected for use at a local level (BCSD projections) followed by land surface modeling (rainfall-runoff) at a basin scale (the VIC model), and finally operations modeling at the river network level (the URGSiM model). Each of these models represents a conceptual simplification of a complex physical system that is imperfectly understood. In addition to the three different model types employed, there are statistical methods employed to connect them. GCM output is statistically downscaled for use in the VIC model and operations model, and statistical methods are used to condition the uncalibrated land surface model output for use in the operations model. Output from each model carries with it uncertainties associated with simplification and lack of understanding of the modeled system, and each statistical transformation of the output increases these uncertainties. By definition, these uncertainties are difficult to quantify, but can have significant effects on the hydrologic projections generated. Like the emission scenarios, the modeling tools are continually being refined, and, as planning moves forward, the hydrologic projections developed by these tools will have to be reexamined as well.

The uncertainties associated with each step in the URGIA analysis are further explored in Section IV of Appendix D.

4. Impact Assessment: Projected Climate and Water Supply, Demand, and Delivery

This chapter describes the projected changes for the Upper Rio Grande's climate, water supply, demand, and delivery.

Section 4.1 describes the past and current climate in the region, and the processes and forces that drive that climate. That section also presents an analysis of the current trends in climate and hydrology in the Upper Rio Grande Basin—the degree to which the region has already experienced warming, and associated hydrologic changes. Following that is a general presentation of the future climate and hydrology of the region, as determined from climate and hydrology models.

Section 4.2 presents projected changes to water supply, in terms of streamflow, reservoir levels, imported water supply, groundwater recharge, and groundwater discharge to streams. The impacts of climate change on the Upper Rio Grande hydrologic system are a result of changing magnitude, timing, and variability of inflows to the system, coupled with temperature-driven increases to evaporative demands. A series of quad graphs in each subsection presents several aspects of the changes in those locations. Please note that each basin presents an independent analysis and thus uses a different scale.

Section 4.3 addresses water demand and delivery in Colorado and New Mexico.

4.1 Climate in the Upper Rio Grande Basin: Past, Present, and Future

4.1.1 Discussion and Overview of the General Climate Characteristics of the Upper Rio Grande

Climate may be distinguished from weather by the longer timescale, decades as opposed to days or weeks, over which meteorological conditions are considered. Meteorological conditions include temperature, precipitation, solar radiation, wind, atmospheric pressure, and humidity, among others. Evaluations of changes in climate include both natural variability and human-induced long term changes in climate. Natural variability includes multi-year cycles in climate such as El Niño and La Niña, as well as cycles that can occur on even longer time scales (for example, the Pacific Decadal Oscillation). Naturally-caused variations in climate continue to occur into the future along with changes due to increased greenhouse gas concentrations from human activities. A literature review summarizing the current climate of the Upper Rio Grande and climate trends in the southwestern United States is presented in Appendix B.

The Upper Rio Grande Basin is classified as an arid climate, with average annual precipitation in most areas of less than 15 inches (38 centimeters [cm]) except in mountain regions. As previously noted, the majority of the water supply derives from snowmelt in the mountainous areas of the basin headwaters. Local precipitation is bi-seasonal, with the major peak in summer (July to September) and a secondary peak in winter (November to March). Arid spells are typical in spring (April to June) and fall (late September through early November). Temperature and precipitation vary by latitude and elevation within the Upper Rio Grande Basin (Kunkel et al. 2013b). See Section 2.1 for locations of areas described. Although annual average temperatures do not capture the range of annual variability, they do convey the relative temperatures in different subregions within the Upper Rio Grande Basin.

- In the San Luis Valley of Southern Colorado, the average annual temperature is 41 to 45°F (5 to 7 degrees Celsius [°C]) and precipitation averages less than 10 inches (25 centimeters [cm]) per year. In the adjacent San Juan Mountains of southern Colorado, average annual temperatures are as cool as 21 to 30°F (-6 to -1°C), with precipitation in the wettest areas exceeding 40 inches (100 cm) per year.

- The Albuquerque portion of the Upper Rio Grande Basin has an annual temperature of approximately 51 to 55°F (11 to13°C; Figure 10) and receives 11 to 15 inches (28 to 38 cm) of precipitation per year (Figure 11).

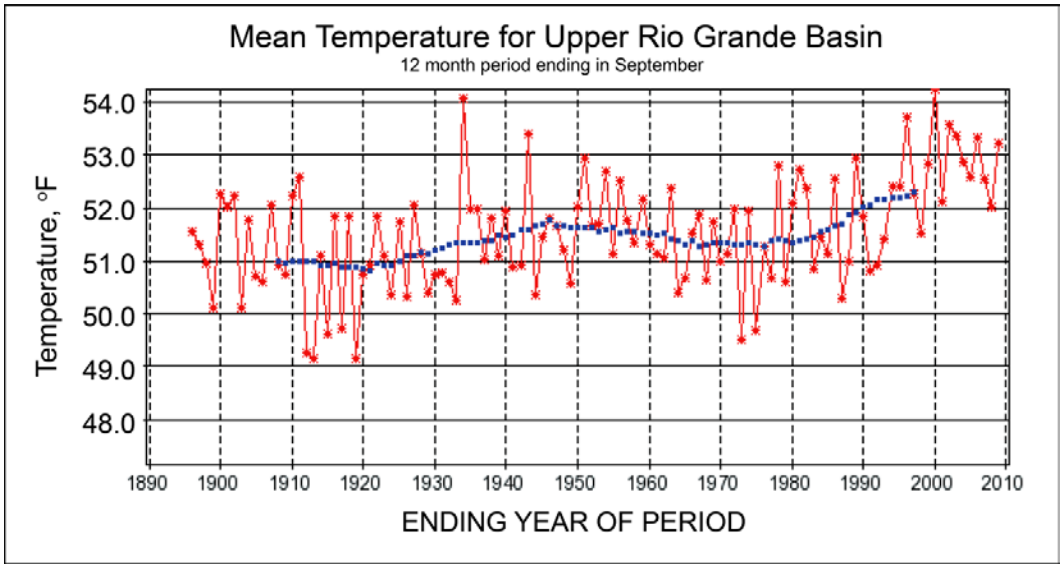


Figure 10.—Observed annual temperature, averaged over the Upper Rio Grande Basin. Red line indicates annual time series for the given geographic region. Blue line is 25-year moving annual mean.

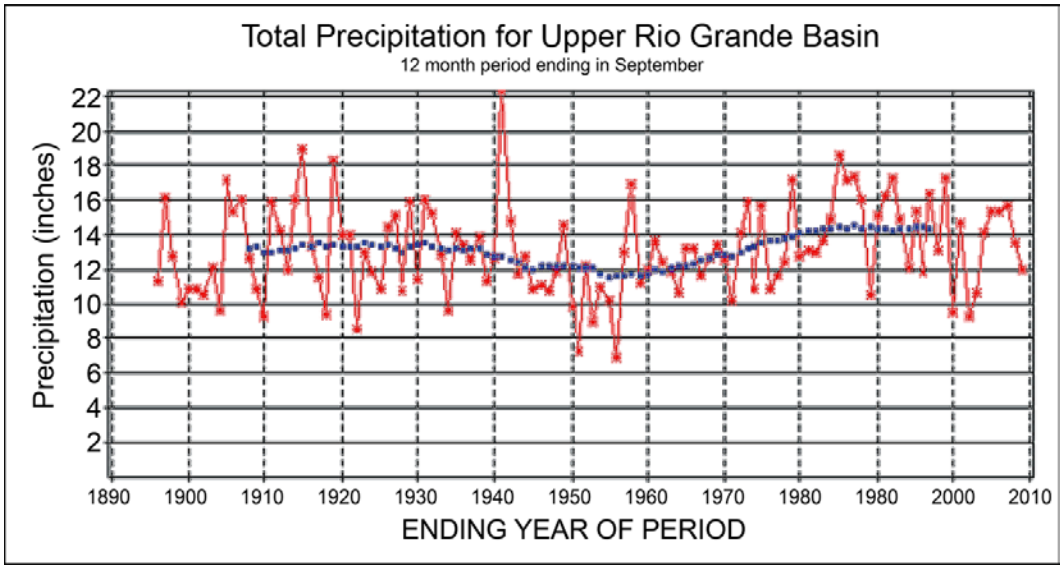


Figure 11.—Observed annual precipitation, averaged over the Upper Rio Grande Basin. (University of Arizona et al. 2007). Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean.

Southern, lower-elevation areas south of Elephant Butte Dam have average annual temperatures of 61 to 65°F (16 to 18° Celsius [°C]), and receive less than 15 inches (38 cm) of precipitation annually.

The basic pattern of New Mexico's climate is driven by its latitude and its position in the continental interior. Solar heating of Earth's surface along the equator causes humid air to rise and to drop its moisture as rain in a band along the equator. A portion of air that has risen at the equator moves north and south at a high altitude, where it cools and eventually descends over the subtropics. As it descends, that air warms and its capacity to retain moisture increases, pulling moisture out of the environment as the air mass descends.[1] The descending dry air returns towards the equator. This convection system moving air between the equator and the subtropics is known as a Hadley Cell (Figure 12). Most of the world's deserts are located at the descending arm of the Hadley Cell, including the Mohave, Sonoran, Chihuahuan, Sahara, Thar, and Saudi Arabia deserts in the Northern Hemisphere, the Atacama, Kalahari, and central Australian deserts in the Southern Hemisphere. The southern portion of the Upper Rio Grande Basin is within the Chihuahuan desert.

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[1] As a general rule of thumb, rising air cools and as it cools, its ability to hold moisture decreases. Thus, the water that rising air contains condenses and eventually precipitates out—so areas underneath rising air get rain. Descending air warms, and as it warms it can hold more moisture, so it becomes relatively drier. Areas underneath descending air do not get rain.

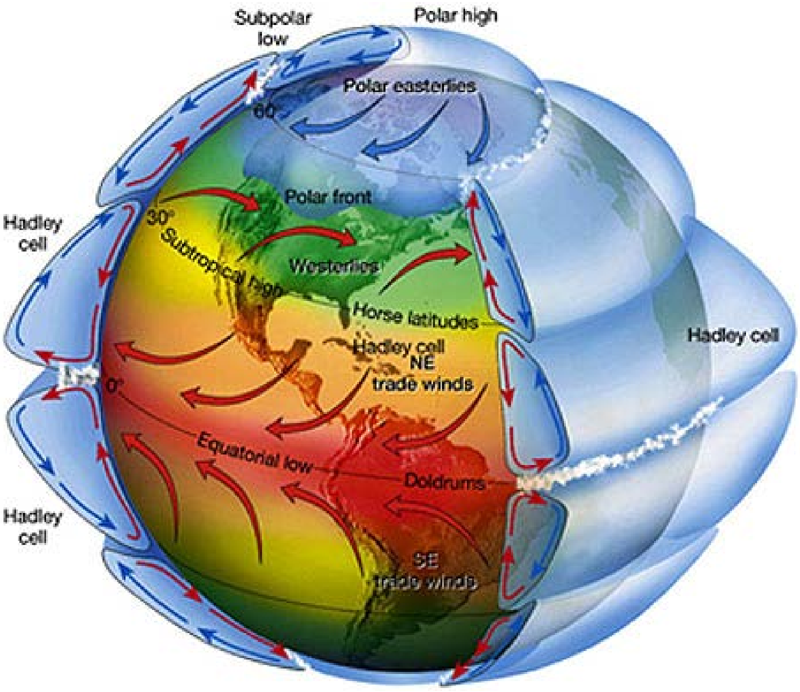

Figure 12.—Atmospheric circulation in the climate system (Hadley cells) (source: National Aeronautics and Space Administration [NASA], nd).

The Hadley Cell in the Northern Hemisphere shifts north in the summer and south in the winter due to the tilt of the earth's axis. During summer months, the northern portion of the descending arm of the Hadley Cell encompasses northern New Mexico and southern Colorado, allowing hot, dry air to settle over the region from March through September. The aridity and heat are reduced in late summer/early fall due to the North American Monsoon, in which diurnal heating of the land surface pulls humid air in from the Gulf of Mexico (sometimes the southeastern Pacific). Heating this air leads to daily convective storms producing intense, localized cloud-bursts. The location of these storms is strongly influenced by topography (with higher elevations tending to have more reliable monsoonal precipitation than lower elevations), and latitude (with southeastern Arizona inside the core monsoon region and the Upper Rio Grande outside of that region). Precipitation during the summer monsoon is characteristically more than 50 percent of the annual local precipitation total in the lower elevation portions of the Upper Rio Grande. The North American Monsoon tapers off in fall as diurnal heating is reduced, although remnant Tropical Pacific cyclones can bring sustained precipitation to the region, especially in September.

With the onset of winter, the area of maximum heating shifts south of the equator, which causes the northern limit of Hadley Cell circulation to shift south of the study area and enables the jet stream to push mid-latitude cyclonic storms into the region. These storms precipitate rain and snow over wide areas, and alternate with high pressure systems that bring dry, sunny weather to the region. However, the amount of precipitation from these systems is limited because the Upper Rio Grande is in the interior of North America: it is surrounded by dry land and is distant from warm oceans. This limit is exacerbated by the region's location in the rainshadow of the Sierra Nevada mountains: much of the moisture coming off of the Pacific is wrung out of storm systems as they cross the Sierras, and is only added back in when these storms reach the Plains states and tap into humid air masses originating over the Gulf of Mexico. As a result, winter precipitation across most of the region is less than summer.

4.1.1.1 Overview of Winter Climate in the Upper Rio Grande Basin

Winter precipitation in the Upper Rio Grande Basin varies from year to year depending primarily on the Pacific Ocean sea surface temperature. Areas of the ocean with warm sea surface temperatures add a great deal of heat (energy) and moisture to overlying air masses, creating larger storms with greater precipitation potential. Areas with cool sea surface temperatures fail to heat the air much, and these areas produce small, weak storms with low or no precipitation potential. Ocean temperatures in areas that matter for Southwestern climate—the eastern Pacific and the Gulf of Mexico—vary in temperature from year to year, with direct consequences for climate in the Upper Rio Grande.

The most familiar variation in ocean temperature (and in the overlying atmosphere) is the El Niño-Southern Oscillation (ENSO) cycle. In a normal (ENSO-neutral) year, surface winds push warm equatorial Pacific surface waters to the west, creating a pool of warm water near Indonesia and allowing very cold, deep ocean water to rise to the surface in the eastern Pacific from northern Peru to Mexico. Over the warm pool, heat and moisture are contributed to the air, the warm air rises, and heavy precipitation occurs in the western Pacific. At the same time, the air over the eastern Pacific is comparatively cool and dry, and therefore the eastern Pacific and adjacent regions (such as the Southwest) are relatively cool and dry.

In an El Niño year, the warm pool "migrates" to the east, leaving Indonesia cooler and drier, and shutting off the upwelling of cold ocean water in the eastern Pacific. Although most precipitation occurs out to sea, there is a significant increase in atmospheric moisture in the eastern Pacific, which brings more winter precipitation to the Southwest. Winter 2009-2010, in which the snowpack was at near-normal levels, was an El Niño year.

ENSO has a third state known as La Niña. In a La Niña phase, the warm pool migrates to the west of its normal position, bringing additional rain to Indonesia and Australia while at the same time bringing hyper-dry conditions to the eastern Pacific. Winter 2010-2011, which was a La Niña winter, was exceptionally warm and arid in the Southwest. Snowpacks in the basin were well below normal.

The frequency of El Niño and La Niña events has increased since the 1970s. Before 1970, El Niño and La Niña events occurred in roughly equal frequencies, and were separated by several normal (ENSO-neutral) years. Since the late 1970s, the frequency of El Niño and La Niña events has increased, El Niño events have outnumbered La Niña events by 2:1, the number of “normal” years separating the two have decreased, and El Niño events have increased in strength. The reasons for these changes are poorly understood. They may relate to other large-scale climate phenomena, including long-cycle changes in sea surface temperatures in the north Pacific which operate on multi-decadal (50-80 year) cycles, and which can serve to amplify or dampen the different phases of the ENSO cycle. Since the 1970s, Central Pacific El Niño events have become more common, in which the warm pool occurs in the central rather than eastern Pacific. During Central Pacific El Niño events, precipitation in the U.S. is reduced relative to Eastern Pacific El Niño events, leading to winter precipitation in the Upper Rio Grande that is at or only slightly above normal (Jin-Yi and Yuhao 2013). Since 1990, five of the last seven El Niño events have been Central Pacific El Niño events.

ENSO effects on precipitation in the Southwest are primarily a winter phenomenon, and summers are usually characterized by ENSO-neutral or transition states. NOAA maintains a regularly updated discussion of current ENSO status, near-term (about 6 month) ENSO projections, and implications for how changes in ENSO would affect temperature and precipitation across North America.

The strength of El Niño and La Niña are also affected by the interplay of long- and short-term climate cycles. Long-term wet and dry cycles in the Southwest are controlled primarily by Pacific sea surface temperatures (SST), particularly the multi-decadal Pacific Decadal Oscillation (PDO), and Atlantic SSTs via the Altantic Multidecadal Oscillation (AMO). The phase of the PDO in particular acts to amplify and dampen portions of the ENSO cycle. The negative (cool) phase of the PDO enhances La Niña effects and dampens the increase in precipitation during El Niño events while the reverse is true under during positive PDO cycles. The PDO has been in a negative phase since May 2010 (Mantua 2013). Historically, the driest periods in the Southwest were associated with cool Pacific SSTs (negative PDO) and warm Atlantic SSTs (positive AMO) (McCabe et al. 2004).

4.1.1.2 Overview of Summer Climate in the Upper Rio Grande Basin

Summertime precipitation and temperature in the Upper Rio Grande Basin is dominated by the North American monsoon. The North American Monsoon is driven by daytime heating of the land surface that, in turn, warms the lower atmosphere leading to atmospheric convection. The rising air cools and, if moisture is present, can lead to precipitation. The monsoon is initiated in mid-summer when surface heating is strong enough over a large enough area to draw in moisture from the Gulf of Mexico and, secondarily, the eastern Pacific/ Gulf of California. The monsoon onset is time-transgressive, beginning mid-June in areas in the southern part of the Southwest and in mid-July in areas in the north. Monsoon strength increases with elevation, in direct proportion to the amount of increase in daytime air mass rise.

The strength of the monsoon varies greatly from year to year for reasons that are not well understood. The strength of the monsoon appears to depend on:

1) How hot the Southwest gets (i.e., how much heat is available to drive air convection)

2) How warm the sea surface temperatures are in the eastern Pacific and Gulf of Mexico, which serve as the principal sources for moist air and therefore determine the amount of moisture in air masses being pulled into the Southwest

3) How active the cyclone/hurricane season is in the eastern Pacific and Gulf of Mexico, which can push tremendous amounts of moisture into the Southwest during the late summer and early fall

Monsoon strength is also affected by sea surface temperatures at the hemispheric scale that govern large-scale movements of air masses at different latitudes. The specific controls on interannual variations in monsoon strength are not well understood.

Monsoon precipitation is typically intense but localized, and rarely has a uniform effect across a large drainage basin area, such as the Upper Rio Grande. However, precipitation can be more widespread if the monsoon is able to tap moisture from a tropical cyclone in the moisture source regions.

4.1.2 Observed Trends in Climate

For the entire Upper Rio Grande study area, temperatures increased substantially from 1971 through 2012, with the average annual temperatures increasing by 2.5°F. Nighttime low temperatures increased faster than the daytime high temperature, 2.7 °F vs. 1.8 °F, respectively (Table 1). Precipitation was unchanged at the regional scale. Mountain and valley regions responded differently to warming, with average temperatures in the mountains increasing by 2.7°F, but average temperatures in the valleys increasing by only 1.6°F over the

Table 1.—Median rates of temperature change (°F per decade) for different time periods

		Early 1971-2000	Late 2001-2012	1971-2012
Tmax	Mountains	0.31	0.70	0.25
	Valleys	0.45	-0.23	0.61
	Region	0.40	0.45	0.45
Tmin	Mountains	1.12	3.15	1.21
	Valleys	0.65	-0.68	0.50
	Region	0.76	1.35	0.67
Tavg	Mountains	0.76	1.93	0.67
	Valleys	0.70	-0.13	0.59
	Region	0.65	0.13	0.63

same period. The change in the mountains was driven by increases in nighttime low temperatures whereas the change in the valleys was driven by increases in both nighttime low and daytime high temperatures.

The rate of temperature change (°F/decade) was not constant over the period 1971 through 2012 (Table 1). In the 11 years beginning in 2001, the trend in maximum and minimum temperatures has been negative in valley areas. By contrast, mountain regions have been characterized by accelerated increase in warming. It is not immediately clear what is driving these changes.

Geographically, the amount of change documented in mountain temperatures was greater in the more northern portions of the Upper Rio Grande Basin.

Temperatures in the Tusas Mountains in the north (which run from the Colorado-New Mexico border south to the Rio Chama Valley) increased by 5.84°F on average, while temperatures in the Jemez Mountains in the south increased at about a quarter of that rate over the same period.

Among valley sites, the greatest temperature increases were measured at sites in the Middle Rio Grande, where average temperatures increased by 0.88°F per decade from 1971 through 2012.

Increasing minimum temperature and decreasing precipitation in March and November are important changes identified by the trend analysis because these contribute to a longer growing season and decreased period of snowpack accumulation in winter months.

The monthly patterns of change in mountain and valley minimum temperature are similar, but differ in magnitude. Two factors may be at play. Valley minimum temperature is affected by cold air drainage; under warming, nighttime inversions may be becoming more frequent (Daly et al. 2010) and this may reduce the rate of gain in valley minimum temperature. By contrast, warming in mountain areas in the presence of soil moisture or snowpack contributes to daytime evaporation of that moisture; condensation under cooler, nighttime temperatures releases heat in the atmosphere and may contribute to faster nighttime warming in higher altitude settings, particularly in winter (Rangwala 2012).

4.1.3 Future Changes in Climate

In future years, more pronounced changes are anticipated in the climate in the Upper Rio Grande, including greater increases in average temperature, earlier snowmelt runoff, and increased variability in streamflow and other hydrologic variables. Projected changes in the climate and hydrology of this region were summarized in the SECURE Water Report (Reclamation 2011a). The projections summarized in that report were developed from the WCRP CMIP3 climate projections, which were bias-corrected and spatially downscaled to this region <http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections>. The results project that the mean-annual temperature would increase by 5 to 7°F during the 21st century (Figure 13). The range of annual variability between the projections among the CMIP3 simulations widens through time.

There is significant disagreement among the climate projections regarding the likely change in annual precipitation over the region. However, the combined mean from numerous projections suggests that mean-annual precipitation, averaged over the Upper Rio Grande, would gradually decrease during the 21st century. The projections also suggest that the annual precipitation in the Upper Rio Grande Basin will remain quite variable over the next century (Figure 13, Panels C and D). More frequent rainfall events and less frequent snowfall events are projected within the Upper Rio Grande Basin.

Warming temperatures are 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., spring through early summer). Although increases or decreases in cool season precipitation could offset or amplify changes in snowpack, it is apparent that the projected warming in the Upper Rio Grande Basin tends to dominate projected effects. Snowpack decreases are expected to be more substantial over the lower-lying portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming.

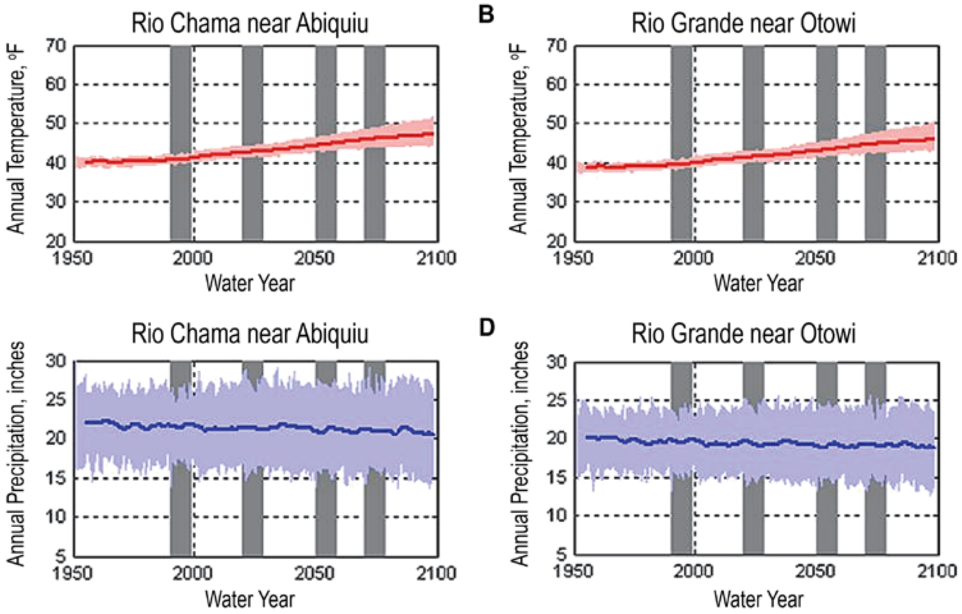

Figure 13.—Simulated annual climate averaged over Rio Grande sub-basins.

Changes in climate and snowpack within the Upper Rio Grande Basin would change the availability of natural water supplies. These changes, which are described in the following sections, may be due to annual runoff or to runoff seasonality. For example, warming temperatures alone (without any changes in the amount of precipitation) would lead to increased ET from the watershed and decreased annual runoff. Increases or decreases in precipitation (either rainfall or snowfall) would offset or amplify the effect.

4.2 Impacts of Climate Change on Water Supply

This section of the report summarizes simulation results that describe impacts on water supply, including basin inflows of native water, inflows of imported water (from Reclamation's San Juan-Chama Project, see Section 2.1.1.1), and groundwater recharge and discharge.

Overall, climate change is projected to significantly decrease available water supplies in the Upper Rio Grande Basin. Supplies from all native water sources to the Rio Grande are projected to decrease by an average of about one third, while flows in the tributaries that supply the San Juan-Chama Project are projected to decrease by an average of about one quarter over the course of the 21st century. In all cases, projections show an increased variability in both monthly and annual flows as the simulations progress into the future. The amount of flow in each season changes dramatically for the Colorado headwaters, the Chama and Jemez Rivers, and the San Juan-Chama Project tributary flows.

4.2.1 Native Basin Inflows

As discussed in section 2.2.1, the native supply of streamflows to the Upper Rio Grande system can be separated into three major groups:

- Colorado headwater inflows to the mainstem of the Rio Grande
- Inflows from minor tributaries in New Mexico
- Inflows to major (gaged) tributaries in New Mexico, including the Rio Chama (and its tributary the Ojo Caliente) and the Rio Jemez

The following subsections describe the impact of climate change on these inflows to the basin, which provide the water supply for downstream water operations and uses.

4.2.1.1 Colorado Headwaters

Colorado headwater inflows are, for the purposes of this analysis, represented by the measured flows at four stream gage locations used by the Rio Grande Compact (Colorado et al. 1938) and shown in Figure 2 to determine Colorado's delivery obligation to New Mexico, known as the Colorado "index" gages:

- Rio Grande near Del Norte
- Conejos River near Mogote
- Los Pinos River near Ortiz
- San Antonio River at Ortiz

Figure 14 provides the analysis results for the ensemble of simulations for the Colorado headwaters. In Panel A, showing the average annual flow, the lightest shading shows all projections, the darker shading shows the middle 80 percent of projections, and the blue shows the median (5-year average of the median of the ensemble of results from all 112 GCM projections). Overall, the projections indicate that native supplies to the Rio Grande are projected to decrease on average by about one third.

Projections show that:

- **Flows at the index gages would decrease by approximately one-third overall**. The annual average flow at all four gage locations, as depicted by the median of our projections, decreases by about 33 percent from approximately 1,200 cubic feet per second (cfs) from 1950 through 1999 to approximately 800 cfs near the year 2100. This decreasing trend is seen for all flows between the 10th percentile and the 90th percentile of model runs. Increased variability in terms of overall low and high flows can be seen starting in 2000.

- **Peak flows would shift to earlier in the year—from June to May.** The variability of flows increases through time, with April and May being more and more likely to experience flows greater than the maximum flows from 1950 through 1999 for those months as time progresses, even as the overall flows decrease.

- **Most flow decreases would occur between June and September.**

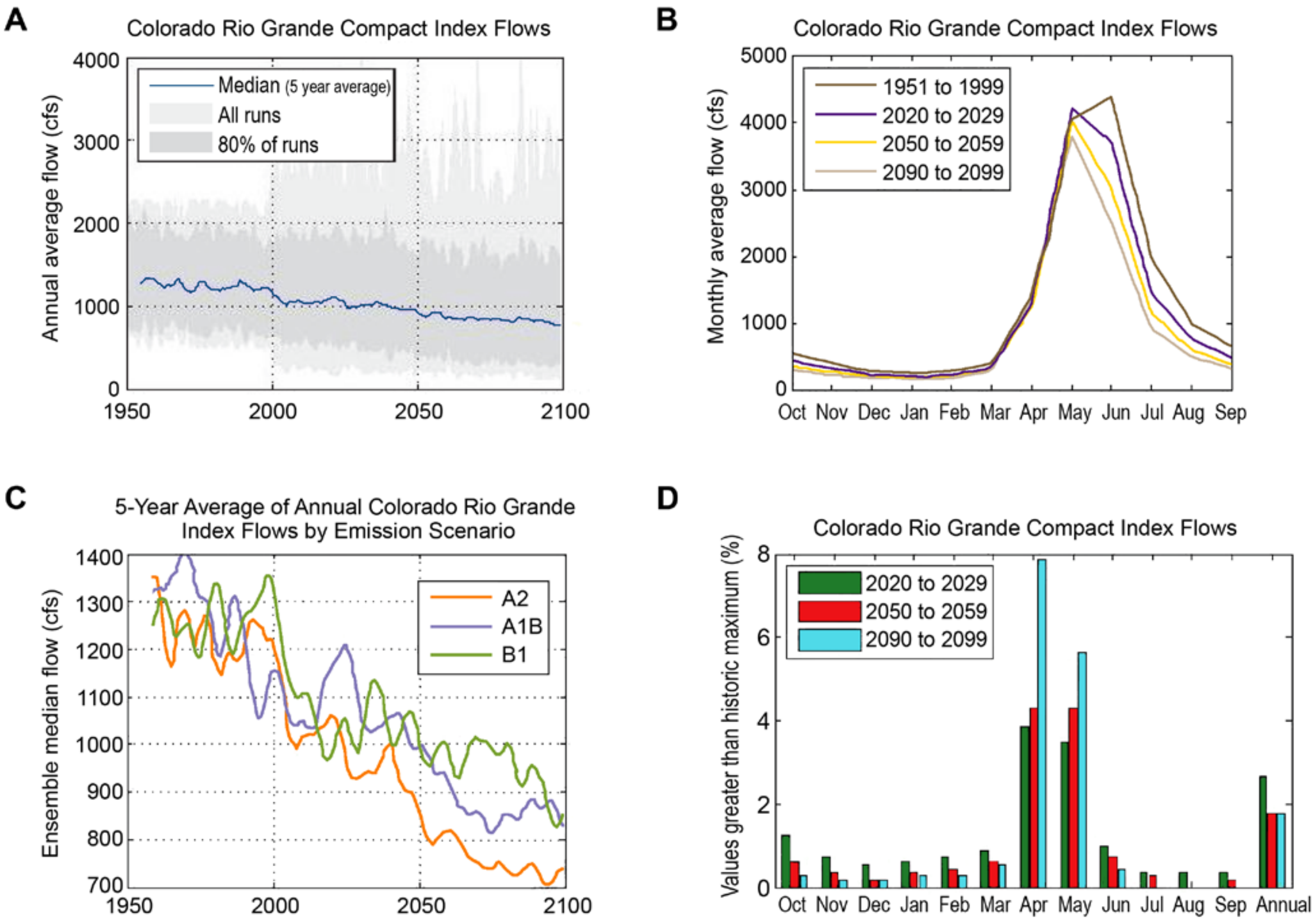

Figure 14.—The projected evolution of flows past the Rio Grande Compact index gages in Colorado.

4.2.1.2 New Mexico Minor Rio Grande Tributary Flows

The minor tributaries included in this group of inflows to the Upper Rio Grande system summarized in this section are: Costilla Creek, Red River, Rio Pueblo de Taos, Embudo Creek, Rio Nambe, Santa Fe River, Galisteo Creek, Tijeras Arroyo, South Diversion Channel, and Rio Puerco. Figure 15 provides the analysis results for the ensemble of simulations for these inflows.

Projections show that:

- **Inflows would decrease by one-third overall**. As with the Colorado headwater inflows, the inflows to the Upper Rio Grande from these sources is projected to decrease by approximately one third (Figure 15). An average total inflow of about 275 cfs from 1950 through 1999 decreases to about 175 cfs by the year 2100 (Figure 15, Panel A).

- **Peak inflow timing would not change.** Interestingly, the shape of the hydrograph of these summed inflows shown in Figure 15, Panel A, does not vary—it simply decreases in all months. The timing of Colorado's deliveries to New Mexico are related to the Rio Grande Compact and are not necessarily coincident to the timing of snowmelt and runoff. There are more southerly tributaries that are less snowmelt-driven. The B1 (low emissions) scenario is distinctly different from the other two emissions scenarios (Panel C), and the added volatility in the future is spread throughout all months of the year (Panel D). These aspects of the simulated flows distinguish the New Mexico minor tributaries to the Rio Grande from the other supply groups considered here.

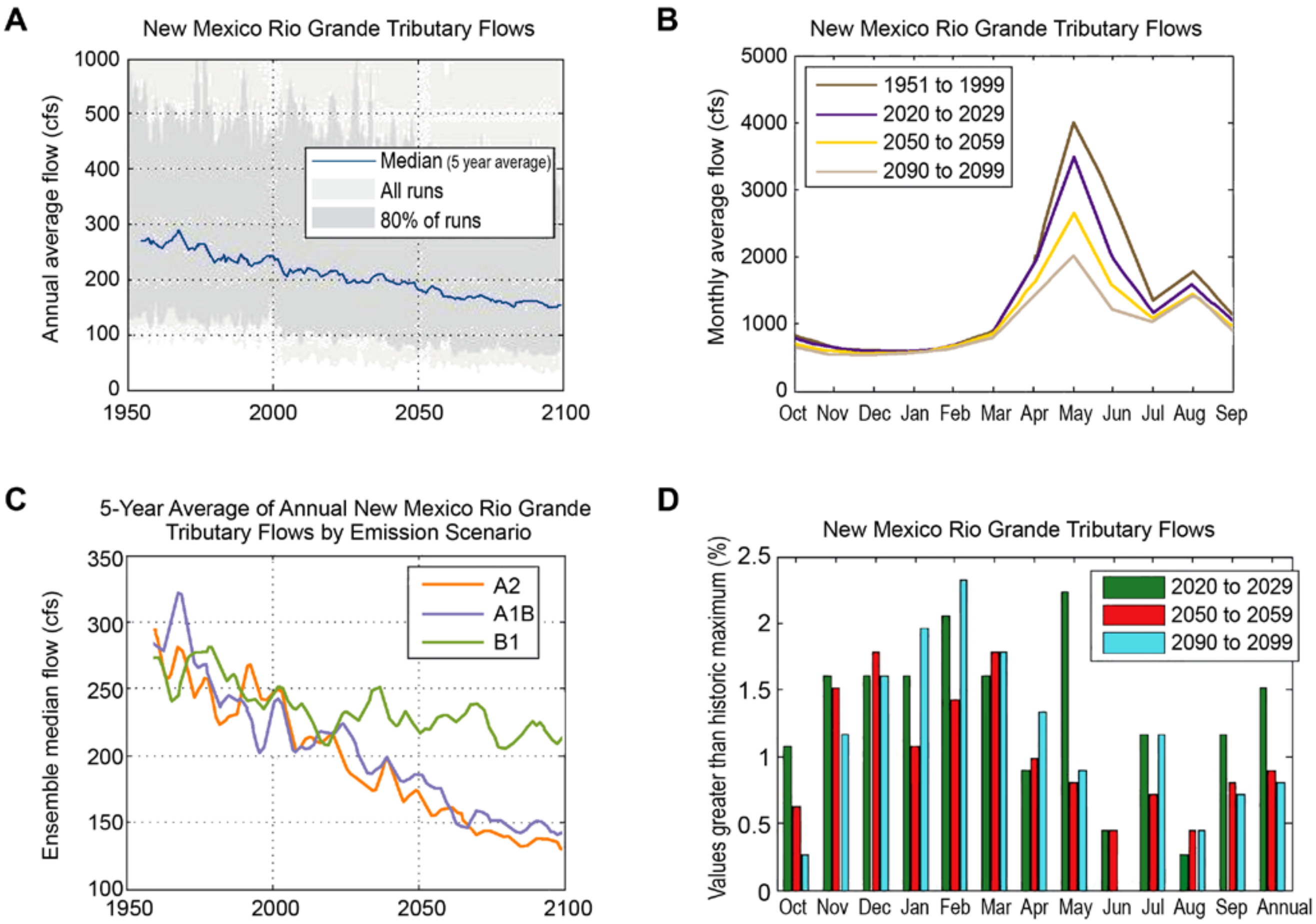

Figure 15.—The projected evolution of Rio Grande tributary inflows in New Mexico (not including the Rio Chama or Rio Jemez inflows).

4.2.1.3 Native Chama and Jemez Inflows

A third grouping of significant surface water inflows to the Upper Rio Grande includes the Rio Chama and its tributary, the Ojo Caliente, and the Rio Jemez. Figure 16 provides the analysis results for the ensemble of simulation for these inflows.

Projections indicate that:

- **Inflows would decrease by one-third overall.** As with the Colorado headwater inflows and the other Rio Grande tributaries in New Mexico, the model inflows from the Rio Chama and the Rio Jemez also decrease by approximately one third between the historic period and the end of the model runs. Median simulated flows of about 450 cfs from 1950 through 1999 period drop to about 300 cfs by the year 2100 (Figure 16, Panel A).

- **Peak spring flows would occur earlier in the year—from May to April.** Average flows in May decrease while average flows in April increase as the simulations progress (Figure 16, Panel B). The added volatility in the future is most noticeable during the winter and spring months (December through April), and limited during the summer months (June through September; Figure 16, Panel D).

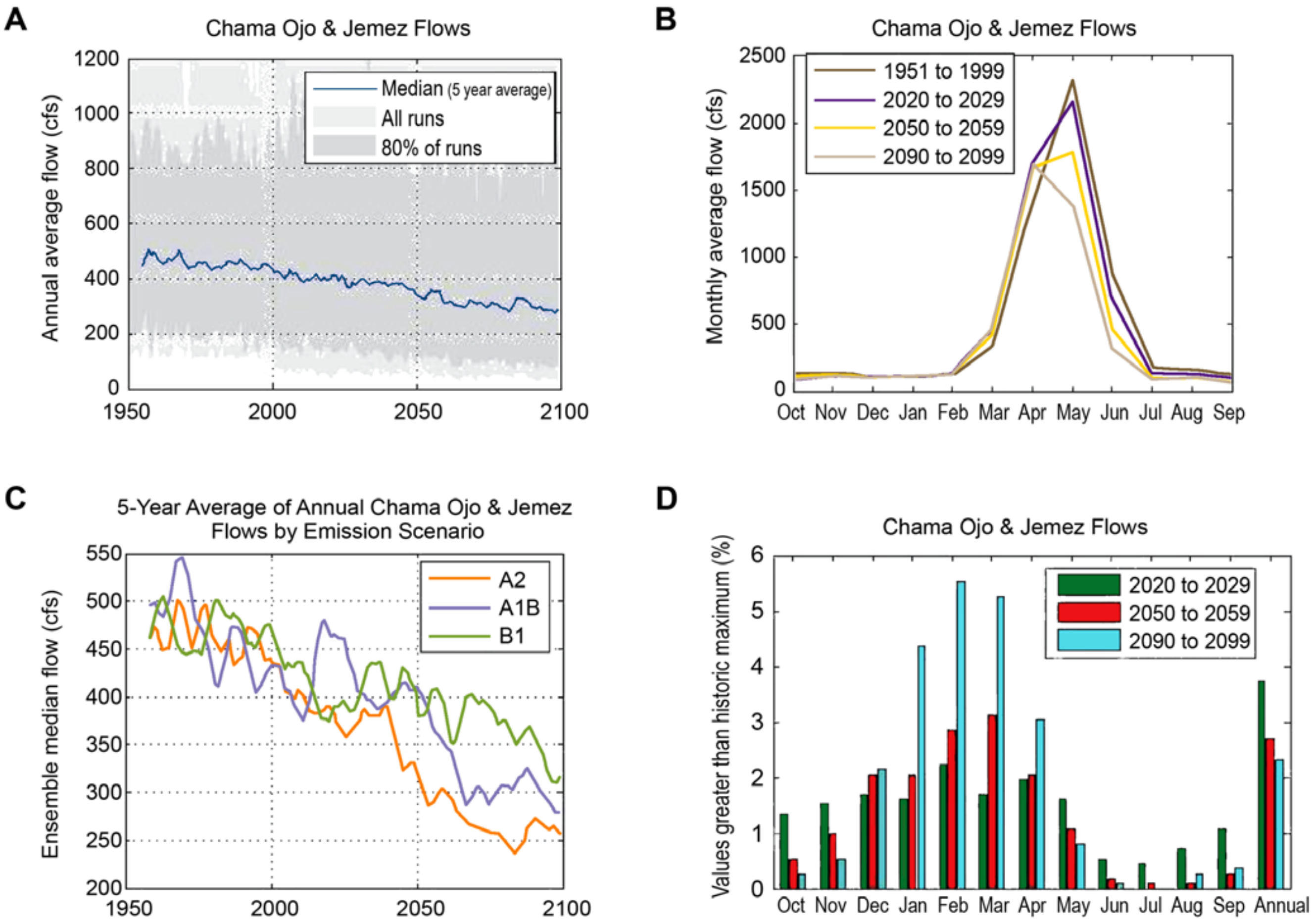

Figure 16.—Projected inflows on the Rio Chama, Rio Ojo Caliente, and Jemez River.

4.2.2 Imported Water: The San Juan-Chama Project

Reclamation's San Juan-Chama Project brings a portion of New Mexico's allocation under the Colorado River Compact into the Rio Grande system. The system, shown in Figure 17, diverts water from tributaries to the San Juan River, through the Azotea Tunnel and stores that water in Heron Reservoir, from where it is distributed. The San Juan-Chama Project supply depends on flows in three tributaries to the San Juan River: the Rio Blanco, the Little Navajo River, and the Navajo River. The project allocates 95,831 acre-feet of water per year to its contractors (369 acre-feet per year of the 96,200 acre-foot per year firm yield is currently unallocated).

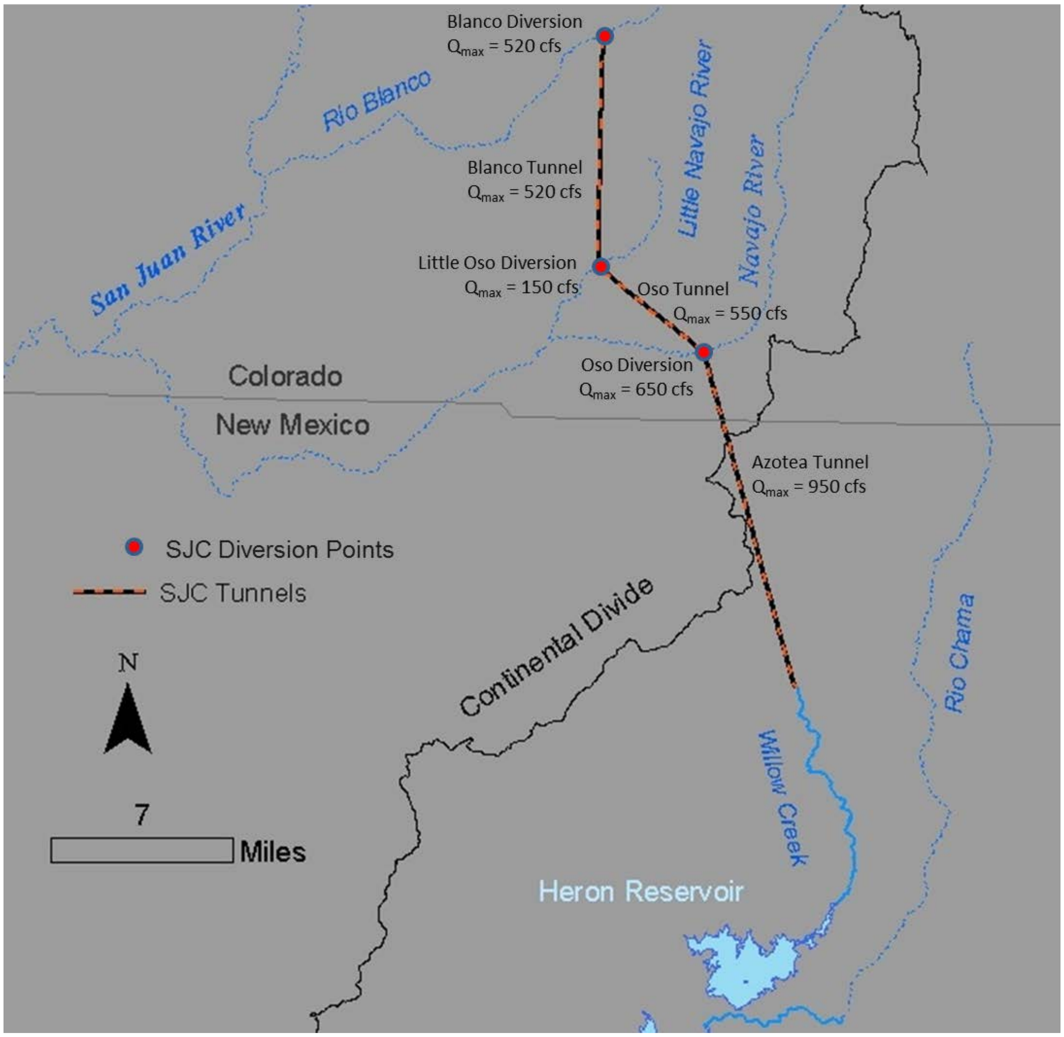

Figure 17.—Location and capacities in cfs of San Juan-Chama Project diversions and tunnels.

4.2.2.1 Diversions

Figure 18 provides the analysis results for the ensemble of simulations for projected flows through the three diversion locations: Oso Diversion on the Navajo River, Little Oso Diversion on the Little Navajo River, and Blanco Diversion on the Rio Blanco.

Projections show that:

- **Flows would decrease by one-quarter overall**. The sum of flows in the three tributaries to the San Juan River is projected to drop by only about one quarter between the historic simulation period (1950 through 1999) and the year 2100, which is less than the one-third reduction projected for native Upper Rio Grande flows. The five-year average of the median flow projection decreases from approximately 225 cfs between 1950 and 1999, to approximately 165 cfs in 2100 (Figure 18, Panel A).

- **Peak flows would shift to earlier in the year.** Total flows at the three diversion locations between February and April increase over the course of the century, as those between May and December decrease (Figure 18, Panel B). By the 2090s, almost 15 percent of simulated March and April flows are greater than any flow observed for those same months between 1950 and 1999 (Figure 18, Panel D).

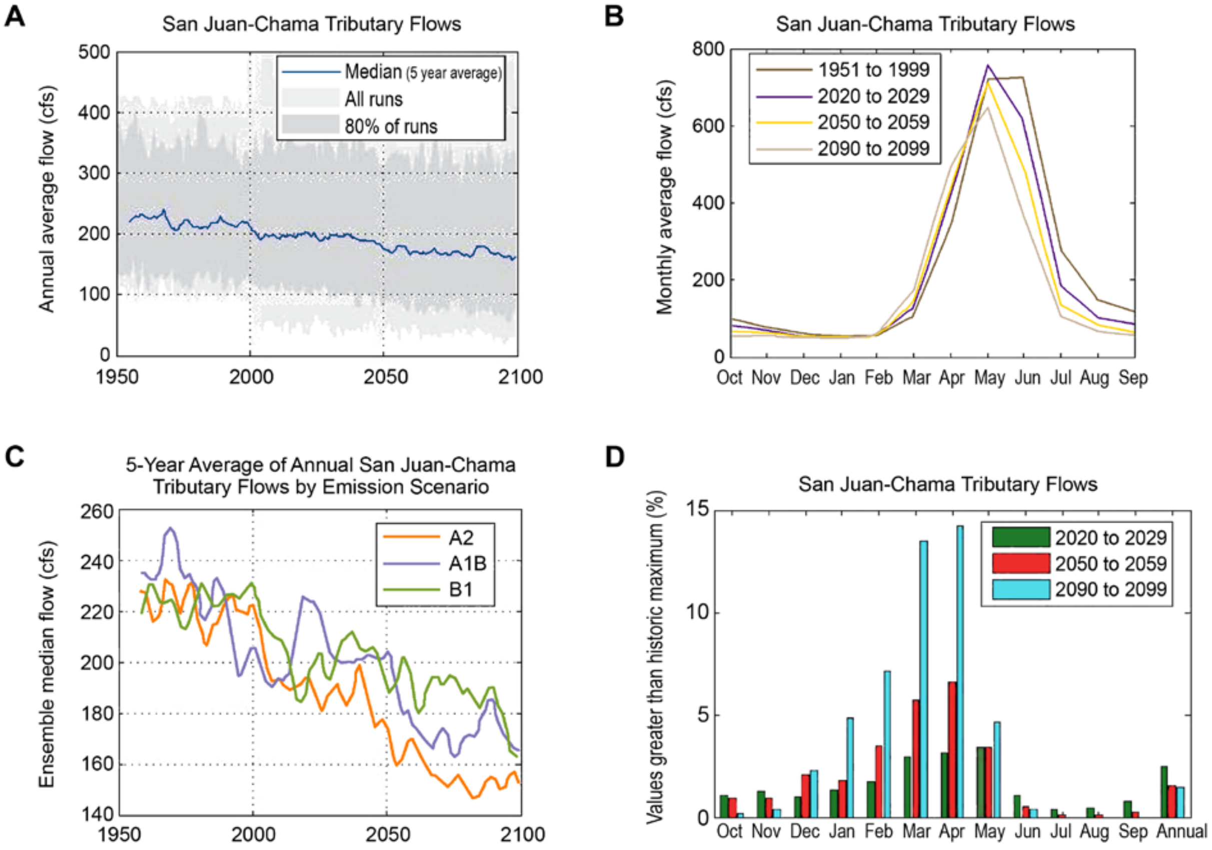

Figure 18.—Projections of total flows from the three San Juan-Chama Project diversion locations on the Rio Blanco, Little Navajo River, and Navajo River.

4.2.2.2 Azotea Tunnel

Figure 19 provides the analysis results for the ensemble of simulations for projected flows through the Azotea Tunnel.

Projections show that:

- **Flows would decrease by one-quarter overall**. The ensemble average trans-basin diversion decreases steadily from around 90,000 acre-feet per year during the historic simulation period (1950 through 1999) to between 70,000 and 80,000 acre-feet per year during the 2050 through 2099 period.

- **Flows would decrease in summer and increase in spring.** Overall, tunnel flows decrease with a larger portion of the flows occurring earlier in the year. The overall reduction in tunnel flows comes from large decreases in divertible flows from May through October even while divertible flows increase in March and April. The seasonality of the average tunnel flows is shown in Figure 19, Panel B.

The analyses on the availability of flows to the San Juan-Chama Project diversion tunnels were performed on a monthly basis. Therefore, these analyses do not capture potential changes to the volume or duration of snowmelt runoff at less than a monthly scale. Since snowmelt runoff is projected to occur earlier, and at potentially higher flow rates for a shorter period of time, the impacts on the San Juan-Chama Project's ability to divert could be larger than shown in this analysis. However, infrastructure changes might be made to allow for a greater capture of short, high-discharge runoffs, so that these changes in runoff flows and timing do not significantly affect the San Juan-Chama Project's ability to divert sufficient water.

Also, it is important to note that, even if sufficient water is available in tributaries to the San Juan River for diversions to the San Juan-Chama Project, shortages within the Colorado River Basin could lead to priority calls or shortage sharing agreements that would result in decreased supply to New Mexico under the Colorado River Compact. Such shortages could result in decreases in Reclamation's authorization to divert water to the San Juan-Chama Project, even if sufficient water is available locally.

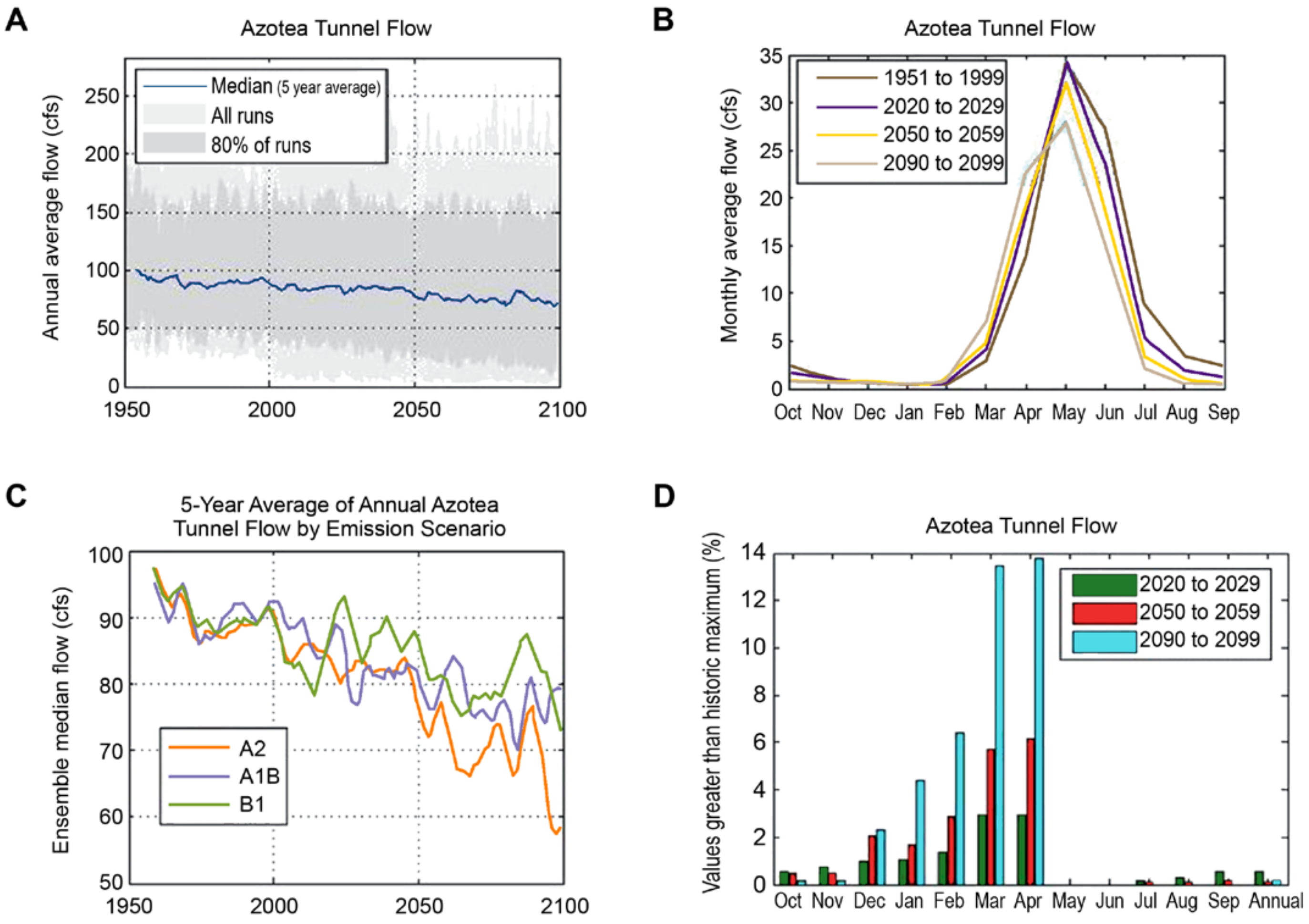

Figure 19.—Projected flows through the Azotea Tunnel of the San Juan-Chama Project.

4.2.2.3 Heron Reservoir

San Juan-Chama Project water is stored in the Heron Reservoir until it is moved downstream for storage or beneficial use. Heron Reservoir storage decreases significantly as the simulations progress, as shown in Figure 20, which displays Heron Reservoir storage on January 1st of each simulation year for the ensemble of simulations. As discussed in the next section, years when Heron Reservoir storage on January 1st is below 95,200 acre-feet result in a reduced initial allocation to San Juan-Chama Project contractors.

Projections show that:

- **Storage in Heron Reservoir would be reduced.** The reduction in storage seen in Figure 20 could be caused by a combination of the decreases in supply noted above and increases in use of San Juan-Chama allocations by contractors as temperature-driven demands in the Rio Grande basin (especially agricultural demands) rise as the simulations progress. However, as seen in Figure 21, San Juan-Chama Project releases from Heron are fairly constant through the first 100 years of simulation and don't show an increasing trend. This suggests that the reduction in storage in Heron Reservoir seen in Figure 20 is predominantly a result of decreased inflows and not as a result of increased outflows.

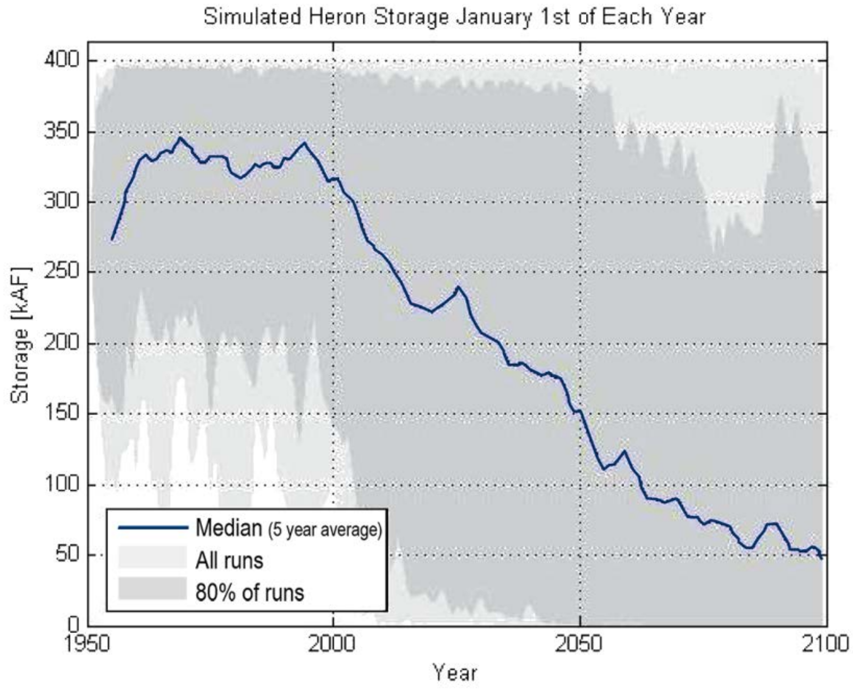

Figure 20.—Projected Heron storage on January 1st of each year.

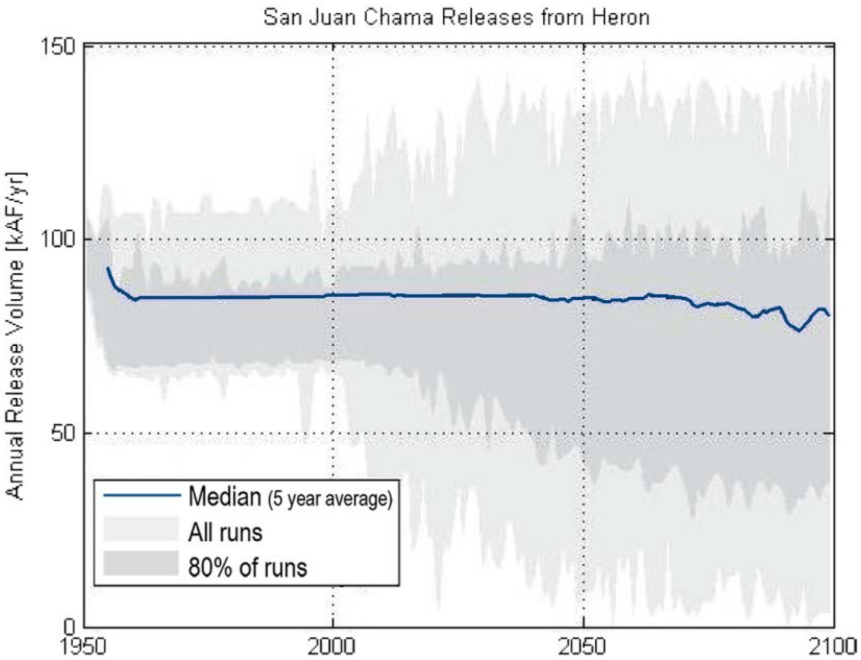

Figure 21.—Projected releases of San Juan-Chama Project water from Heron Reservoir.

4.2.2.4 Impact on Annual Allocations to Contractors

Heron Reservoir storage on January 1st (Figure 20) determines Reclamation's initial allocation of San Juan-Chama Project water to the contractors. If the initial allocation is less than 100 percent of the firm yield, a second allocation may be made on July 1st. This means that any water in storage on January 1st plus any water that can be moved through Azotea Tunnel between January 1st and July 1st can be allocated in a given year to San Juan-Chama contractors. As January 1st storage begins to drop in the simulations, the July allocation becomes more important to the total San Juan-Chama Project allocation.

Three time series showing the distributions of total, January, and July allocations are shown in the left side of Figure 22. As the flows through Azotea Tunnel become less reliable, the initial allocation also becomes less reliable, and the secondary allocation becomes more important. San Juan-Chama contractors receive a full allocation in 99 percent of simulated years from 1950 through 1999, 94 percent during the 2020s, 72 percent during the 2050s, and only 61 percent in the 2090s. At the same time, July allocations go from negligible during the 1950 through 1999 historic period to accounting for almost 40 percent of allocated water during the 2090s. Table 2 summarizes these trends quantitatively, and the right side of Figure 22 visualizes these trends as exceedance probability lines. This table and these figures show that the chances for a full allocation drop almost 30 percent and July allocations rise almost 40 percent.

Table 2.—San Juan-Chama allocations during different simulation periods

Period	Simulations with full San Juan-Chama allocation on January 1	Simulations with eventual full San Juan-Chama allocation (July 1)	Average total San Juan-Chama allocation	Average initial (January 1) allocation	Average secondary (July 1) allocation
1950 - 1999	98%	99%	99.95%	99.5%	0.45%
2020s	72%	85%	94%	81%	14%
2050s	51%	72%	88%	64%	24%
2090s	36%	61%	81%	49%	32%

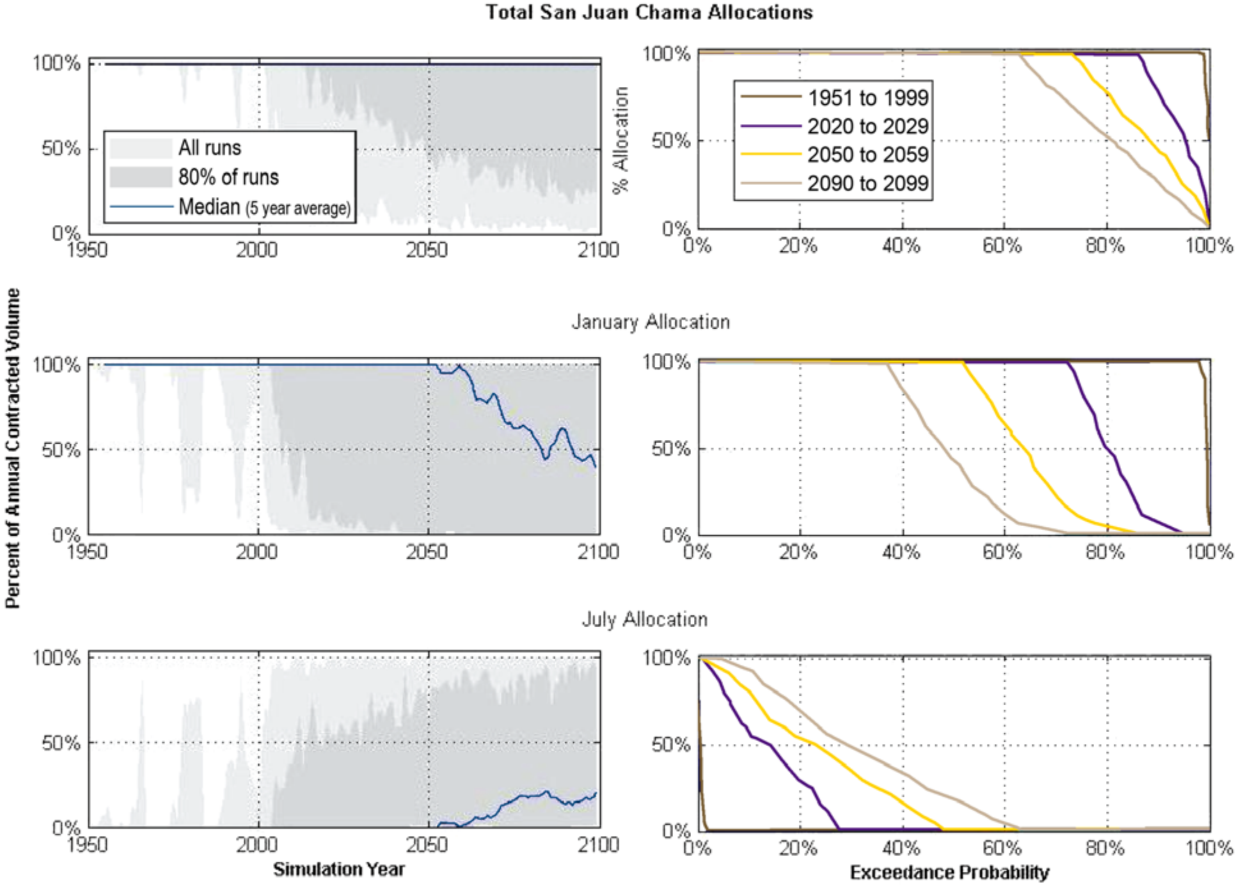

Figure 22.—Projected San Juan-Chama Project total annual allocations (top figures), January (initial) allocations (middle figures), and July (secondary) allocations (bottom figures).

4.2.2.5 Comparison to Previous Yield Estimates and Discussion

Reclamation has estimated the potential firm yield of the San Juan-Chama Project since the 1950s era design phase. By “firm yield,” these studies meant the yield at which there would rarely be a shortage. Reclamation studies in 1964 (Reclamation 1964), 1986 (Reclamation 1986), 1989 (Reclamation 1989), and 1999 (Reclamation 1999), each with a longer hydrologic analysis period than the last, set the firm yield of the project to 101,800; 94,200; 96,200; and 96,200 acre-feet, respectively.

More recently, Roach (2009) performed an analysis using 604 years of tree-ring records developed by Gangopadhyay and Harding (2008). This analysis tracked Heron Reservoir storage as it would have been if the San Juan-Chama Project had been in operation over that 604-year hydrologic sequence. Figure 23 shows the resulting distribution of January 1st storage values at Heron Reservoir. Once the influence of initial conditions wears off, the distribution of possible values is fairly constant. Once this state is reached (about simulation year 2040 in Figure 23), there is approximately a 10 percent chance that Heron would start the year with less than 95,200 acre-feet in storage, and thus that the initial San Juan-Chama Project allocation would be less than the contracted amount less than 10 percent of the time.

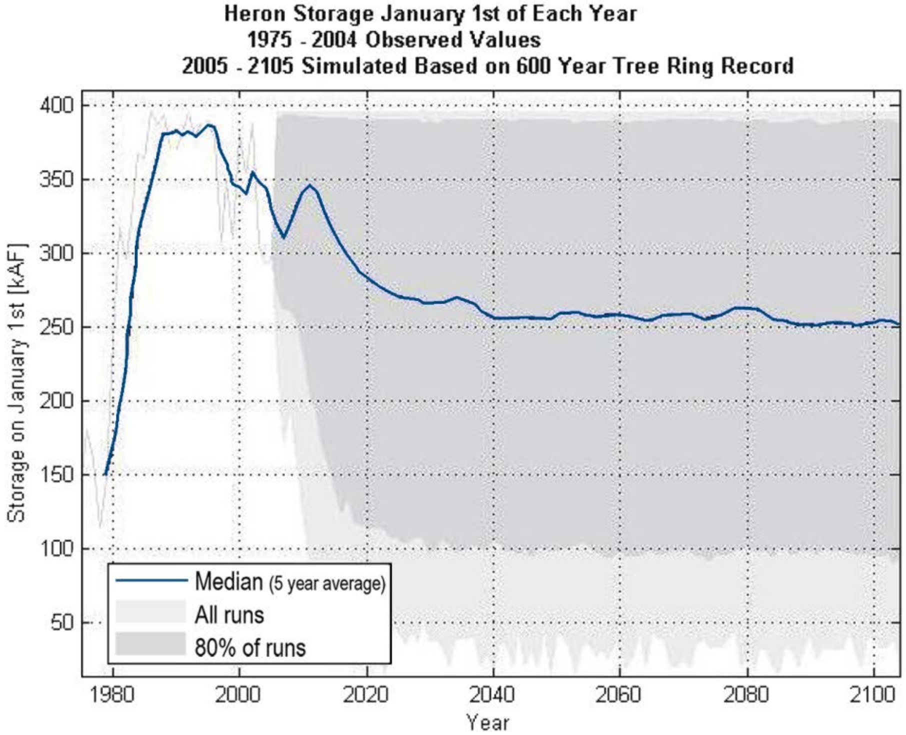

Figure 23.—Simulated Heron Storage on January 1st of a 150-year simulation representing the range of variability of a 600-year tree-ring record (simulated as if the San Juan-Chama Project was in operation for all of those 150 years).

In 2013, for the first time in the 42 years of operation of the San Juan-Chama Project, Heron Reservoir water supplies were insufficient on January 1st to support a complete initial allocation. Although Reclamation was able to provide a full supply July 1st, the supply is less certain for subsequent years. Whether this is just natural variability or a harbinger of things to come (as projected in the URGIA analysis) remains to be seen. This event may prompt an update of the firm yield calculations by Reclamation, and the added hydrologic record since 1999 (the last time the firm yield was evaluated) might itself result in a reduction in the firm yield calculation.

4.2.3 Groundwater Discharge to Surface Water in New Mexico

There are many ways that water can recharge the groundwater system, including aerially, at the mountain front, via seepage through the beds of rivers and streams, and via seepage through the root zone under irrigated agricultural fields (less that amount returned to the surface water system via drain capture). Estimation of how changes to precipitation and temperature predicted in the GCMs would alter precipitation-driven recharge (e.g., Serrat-Capdevila et al. 2007) is an area of on-going research in the West Wide Climate Risk Assessment However, for this study, mountain-front, areal, and tributary-streambed recharge were held constant. The sources of recharge that are expected to undergo the greatest changes in the Upper Rio Grande groundwater system are seepage through the bed of the Rio Grande itself and seepage through the root zone of agricultural fields since the sources of water from these forms or recharge, river flows, and agricultural irrigation are expected to be most affected by climate change. The effects of the changes in groundwater recharge that were include in the operational model simulations to the surface-water system are depicted below in terms of changes to groundwater levels and groundwater discharge in the following section.

Groundwater discharge to the surface water system, where it occurs, can increase surface flows. Such discharge may be directly to the Rio Grande, Rio Chama, or Jemez River, to agricultural drains or to wells through pumping. Figure 24 and Figure 25 provide the analysis results for the simulations for groundwater discharge.

Projections show that:

- **Groundwater levels would decrease.** Shallow groundwater levels decrease slightly through the simulations (Figure 24). This decrease results in a reduction in ET (Figure 25, Panel D) and a decrease in groundwater discharge to the drains.

- **Groundwater recharge would decrease.** At the same time, recharge from both river seepage and crop and canal seepage decreases due to reduced surface flows. The decrease in recharge from the surface water system is offset by the decrease in discharge to the drain system so that net surface water recharge remains fairly constant (Figure 25, Panel B). In the gaining reaches between the Embudo and San Felipe gages, groundwater discharge drops (Figure 25, Panel A), driven by shallow head reduction in the Cochiti to San Felipe reach.

- **Groundwater demand would increase.** Groundwater extraction by Albuquerque and Santa Fe, New Mexico, increases (Figure 25, Panel C) as a result of slightly increased demand (as described in Section 4.3) and reductions in availability of San Juan-Chama Project water, an important surface water supply to municipalities in New Mexico.

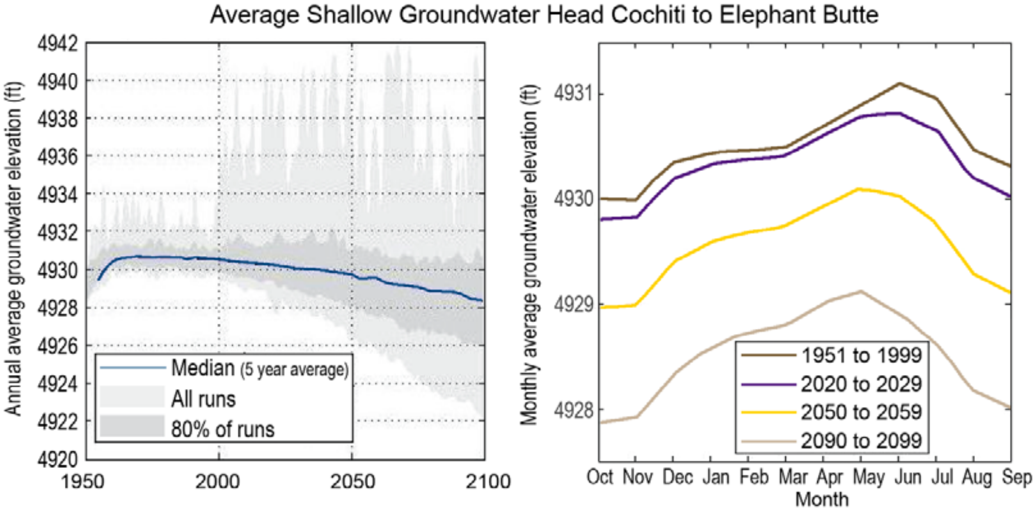

Figure 24.—Projected average water elevation in the shallow groundwater aquifer between Cochiti and Elephant Butte reservoirs.

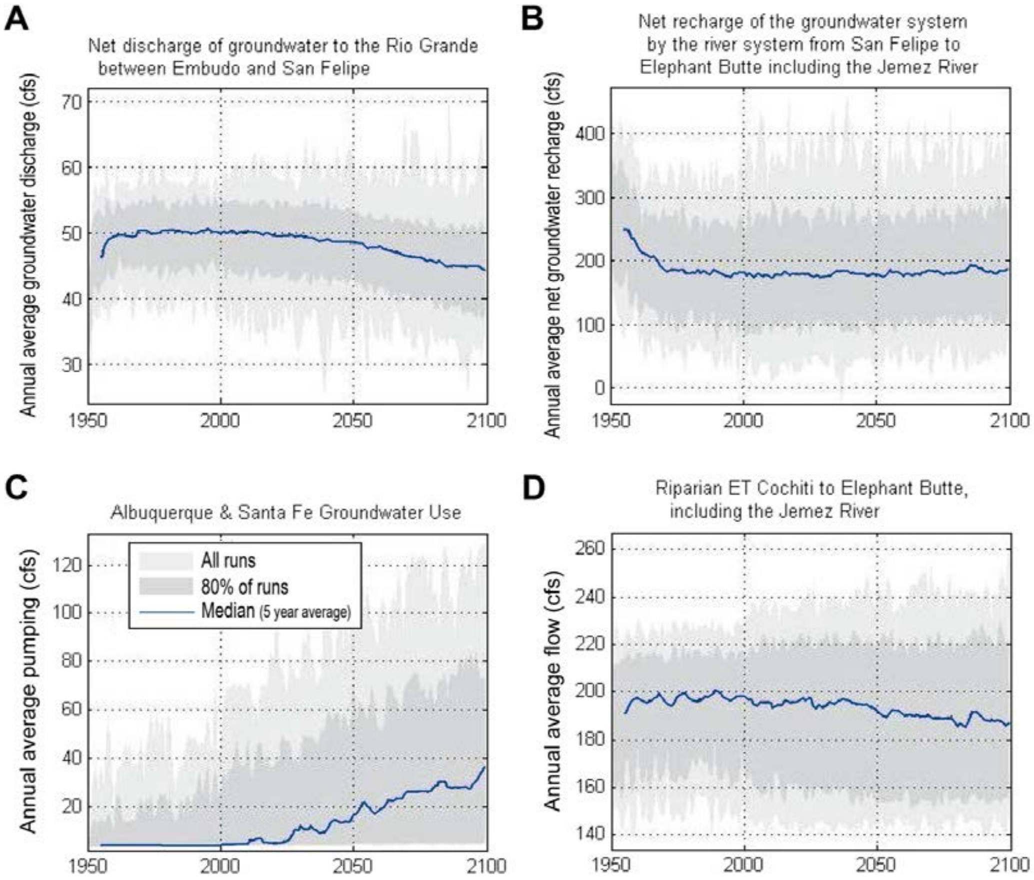

Figure 25.—Groundwater/surface water interaction between Embudo and Elephant Butte reservoirs (Panels A and B) and groundwater discharge via wells and riparian vegetation (Panels C and D).

4.3 Impacts of Climate Change on Water Delivery and Consumption

Sections 4.3.1 and 4.3.3 describe model projections of water delivery by the states of Colorado and New Mexico. Consistent with Reclamation's stated approach for Impact Assessment, the operational modeling used in the URGIA assumes that current water operations are continued unchanged into the future, with no changes in population, agricultural area, riparian area, or other water uses or allocations. As previously explained, this allows the study team to isolate the impacts of climate change from other changes in the basin that affect water supply. Using this assumption, Colorado is modeled to use its ability for priority administration to assure its obligations are met under the Rio Grande Compact (Colorado et al. 1938). This results in significant impacts to modeled irrigated acreage. New Mexico, however, does not currently have a formal process for assuring Rio Grande Compact Compliance; and, therefore, no method is specified in the operations model. Reclamation recognizes that, under the projected hydrologic conditions, New Mexico would take steps to maintain Rio Grande Compact compliance.

4.3.1 Southern Colorado Water Delivery

Inflow projections at the four Colorado index gage locations in the San Luis Basin (known as "index gages" because of their role in the Rio Grande Compact), were described in Section 4.2.1.1. Our analyses of how those index gage inflows are used in Colorado, and thus how much water is passed through the San Luis Valley into New Mexico, were based on the simplifying assumption that Colorado would continue to comply with the Rio Grande Compact. Therefore, this URGIA does not address Colorado's challenges in meeting its delivery obligations under the Rio Grande Compact but does determine the decreases in water use within the San Luis Valley that would be required to maintain Rio Grande Compact compliance.

As was described in Section 4.2.1 and shown in Figure 14, annual average flows at the four index gage locations drops from approximately 1,250 cfs during the historic simulation period of 1950 through 1999 to around 800 cfs by the latter half of the 21st century, a decrease of more than 33 percent. The hydrographs at the four index gage locations described above were used to calculate the flows that would be needed to meet Colorado's Rio Grande Compact deliveries (specific analysis methods are described in Appendix E: URGSiM). Since it is assumed in our model that Colorado would adjust its irrigation diversions so that required deliveries under the Rio Grande Compact are made, flows at the Rio Grande near Lobatos gage, which is near the Colorado/New Mexico state line, are assumed to match the delivery requirement, Figure 26 provides the analysis results for the ensemble of simulations for these flows in the Rio Grande near Lobatos.

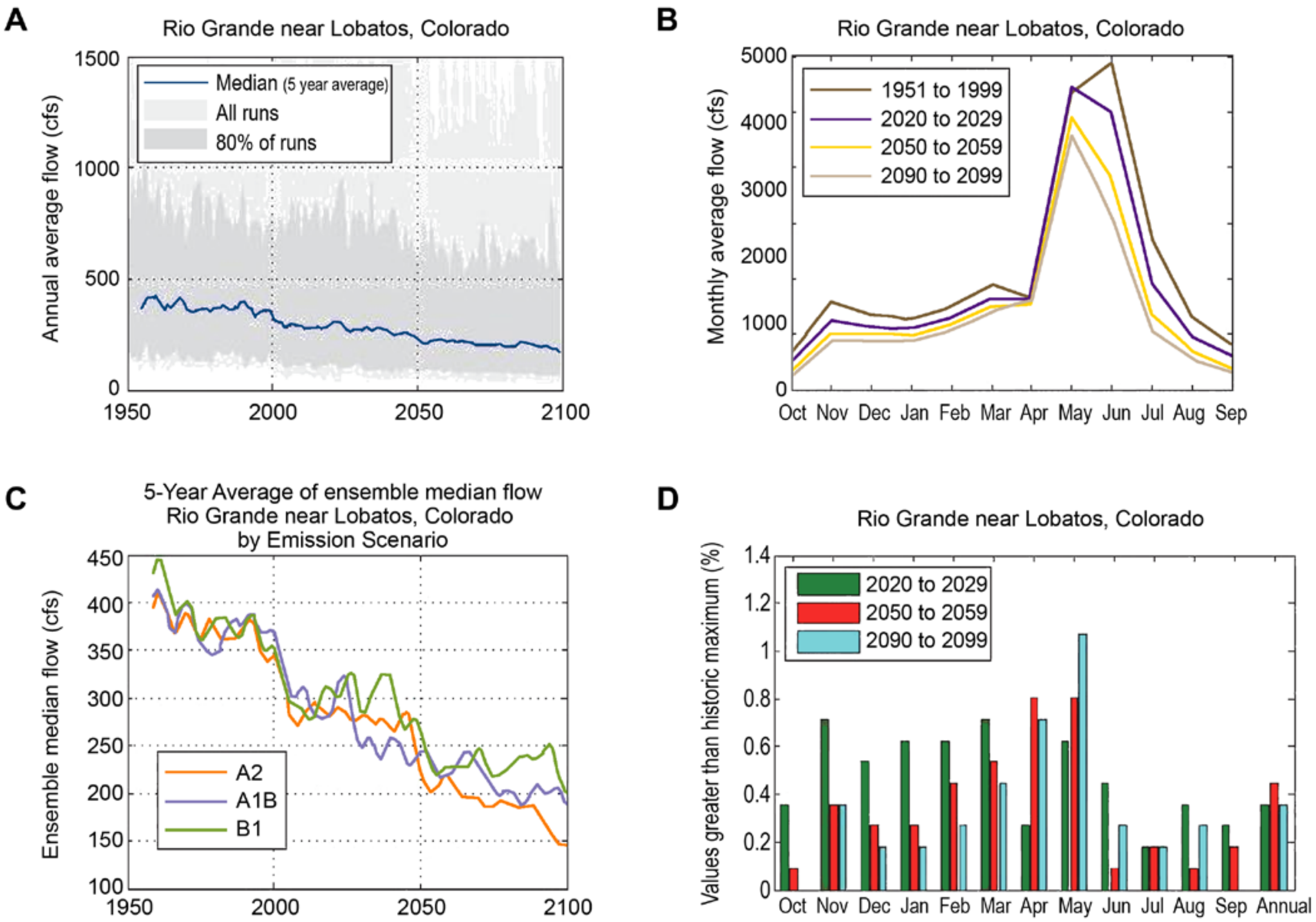

Figure 26.—Projected flows along the Rio Grande near Lobatos, Colorado.

Projections show that:

- **Flows would decrease by 50 percent near Lobatos.** The Rio Grande Compact-driven flows near Lobatos appear to decrease on average from around 400 cfs during the historic simulation to 200 cfs by the end of the 21st century, a 50 percent reduction. The reduction in flows near Lobatos is greater (about 50 percent) than the reduction at the index gages (about 33 percent), suggesting that the Rio Grande Compact structure may buffer consumptive use in the San Luis Valley from changes to supply—at the expense of downstream deliveries to New Mexico.

- **Colorado would maintain compliance under the Rio Grande Compact.** Figure 27 shows Colorado's cumulative Rio Grande Compact balance. A positive value represents a credit (or over-delivery) downstream, while a negative value represents a deficit (or under delivery). As seen in Figure 27, although flow reductions at Lobatos are greater (about 50 percent) than at the index gages (about 33 percent), Colorado's Compact balance stays near zero, and even tends to be slightly positive as the model runs progress. URGSiM is set up to try to match downstream delivery obligations based on the historic average shape of the hydrograph (See Appendix E). As the timing of those flows shift, earlier peak runoff mimics larger runoffs in the historic record, so fools URGSiM into over-predicting annual supply and annual obligation early in the year, and thus to over-deliver on average. This results in a Rio Grande Compact balance that is slightly positive through time.

4.3.2 Southern Colorado Water Consumption

The difference between the total flows at the four Colorado index gages and the delivery obligation under the Rio Grande Compact approximates the amount of Rio Grande and Conejos River water available for consumption in the San Luis Valley. However, this difference does not take into account all local sources that would contribute to the Upper Rio Grande river system below the Colorado index gages, and therefore underestimates the total water available. The flow of the various tributaries to the Rio Grande from the Sangre de Cristo mountain range to the east of the valley can be added as potential consumption, as can any water from Reclamation's "Closed Basin" groundwater pumping project that are pumped into the Rio Grande to help with deliveries to comply with the Rio Grande Compact.

The changes to those sources are beyond the scope of this analysis, and these changes are not considered here. For this reason, the analysis presented here of water available for consumption within the San Luis Valley only indicates changes to consumption of Colorado index gage flows under climate change,

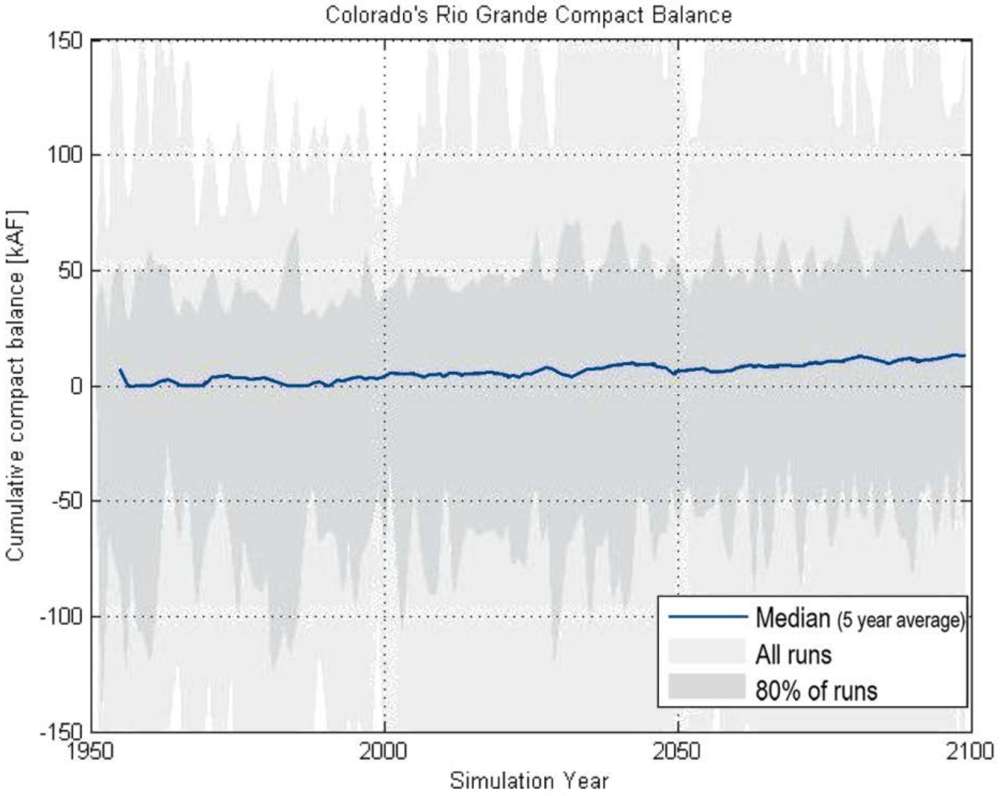

Figure 27.—Colorado's projected balance over time under the Rio Grande Compact.

rather than as representative of the entire San Luis Valley. However, if the reduction to flows predicted at the Colorado index gages does occur, it is likely that these tributaries would be similarly affected. In addition, index gage flows represent a significant portion of the San Luis Valley's renewable water supply, meaning this analysis is an important first step to consider the risks of climate change on water use in the San Luis Valley. Figure 28 provides the analysis results for the ensemble of simulations for southern Colorado water consumption.

Projections indicate that:

- **The amount of water available for consumption would be reduced.** Figure 28 shows the reduction in the amount of water available for consumption in the San Luis Valley (relative to the flow at the four Colorado index gages) for the URGIA projections. As can be seen, the consumption within the San Luis Valley drops from an annual average of about 800 cfs to an annual average of about 600 cfs, a decrease of approximately 25 percent.

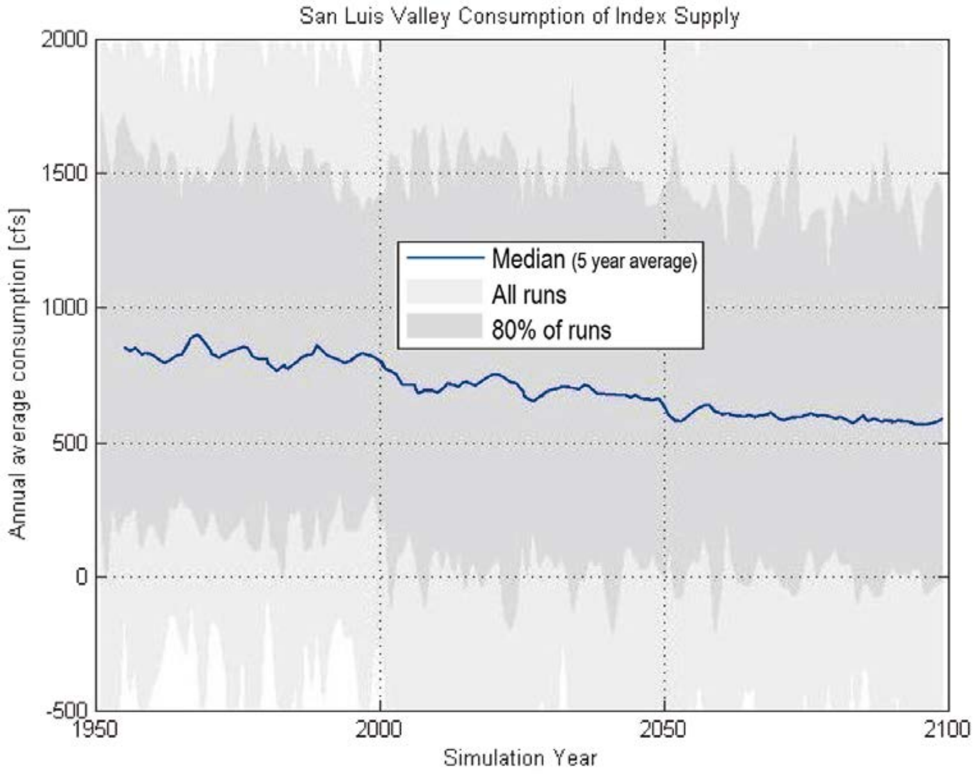

Figure 28.—Projected water consumption in the San Luis Valley from the Rio Grande and the Conejos River.

- **Downstream deliveries would be reduced.** The decrease in water supply at the Colorado Index gages of about 33 percent described above would, in turn, decrease Colorado's delivery obligation under the Rio Grande Compact by an average of about 50 percent. Note that the delivery requirement, and the total water available for consumption shown in Figure 28 do not include water resources in the San Luis Valley that contribute to Rio Grande or Conejos River system flows below the Colorado index gages.

The San Luis Valley is fully adjudicated, and water allocations are administered according to strict priority appropriations, after accounting for downstream delivery obligations. The Prior Appropriation Doctrine states that water rights are determined by priority of beneficial use. This means that the first person to use water or divert water for a beneficial use or purpose can acquire individual rights to the water. A 25 percent decrease in water available for consumption can be mapped directly to water rights that would no longer be served if that decrease were experienced.

Figure 29 shows the number and date of water diversion rights in the San Luis Valley along both the Rio Grande and Conejos River systems. Development on the Conejos River started first, with almost 1,000 cfs of diversion rights established when Rio Grande diversions began to be developed by 1870. Both systems were developed aggressively during the 1880s. The Conejos River was almost fully developed by 1890, with only small additional rights granted from then until the late 1920s when the last diversion rights were developed in that system. The rapid development of Rio Grande diversions also continued through the 1890s, but by the turn of the century, that system was almost fully developed with only minor additional rights granted between then and the early 1950s when the last diversion rights were granted on the Rio Grande. Total developed diversion rights exist for over 3,300 cfs of diversion from the Conejos River and over 5,600 cfs of diversion from the Rio Grande.

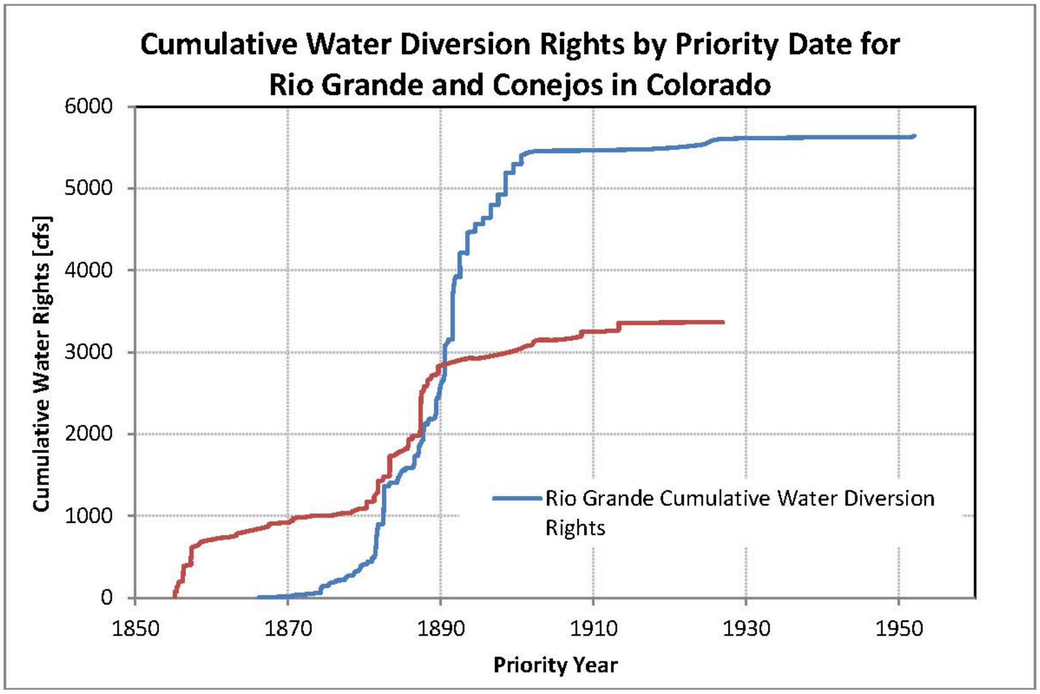

Figure 29.—Size and priority date of water diversion rights on the Rio Grande and Conejos River systems in Colorado's San Luis Valley.

Note: There may be minor differences between this analysis and the actual administration of rights. The data used here and shown in Figure 29 are from the Colorado Division of Water Resources, Alamosa Division (Colorado Office of State Engineer nd). The data provided are ordered according to a priority *number that does not correspond in all cases to the order that would result from the priority date. To make analysis more intuitive; we used the data ordered strictly by priority date. Therefore, this analysis may not correspond to the actual administration of rights in all cases.*

To estimate which water rights would be served with a given amount of water available for consumption within the San Luis Valley, we must make assumptions regarding the percent of the diverted water that would return to the system and become available to be diverted again, and regarding how much consumable water enters the system below the four Colorado index gages. For simplicity, we ignore additional inflows and assume 50 percent return flows, meaning that 500 cfs of internal consumption would serve 1,000 cfs of diversion rights because it would take 1,000 cfs of diversion to result in the 500 cfs of consumptive use. With this assumption and the data plotted in Figure 29, an estimate was made of the priority date of the last water right served in each month of each simulation. Figure 30 (Panels B and D) summarizes these results for each river system for the months of April through September.

Projections show that:

- **Native inflows would decrease.** This analysis suggests that water available for irrigation from native inflows to the San Luis Valley (as measured by gages above major diversions on the Rio Grande, Conejos, San Antonio, and Los Pinos rivers) would be reduced under climate change by an average of about 33 percent by the end of the 21st century. Assuming that Colorado meets downstream delivery obligations specified by the Rio Grande Compact, this supply reduction would reduce the water supply available for consumptive use in the San Luis Valley by about 25 percent and reduce the average downstream delivery to New Mexico by about 50 percent by the end of the 21st century.

- **Fewer water rights would be served.** As changes to flows occur, fewer water rights would be fully served on the Conejos and the Rio Grande. Water supplies from June through the end of the irrigations season are projected to experience the largest declines, and water rights with the most recent priority dates are most likely to experience shortages. The left side of Figure 30 shows the priority dates of water rights for which there would be sufficient water for a full supply every month from May through August. On both rivers, as the century progresses, a more senior water right (i.e., an earlier priority date) is needed to maintain full diversions throughout the heart of the irrigation season.

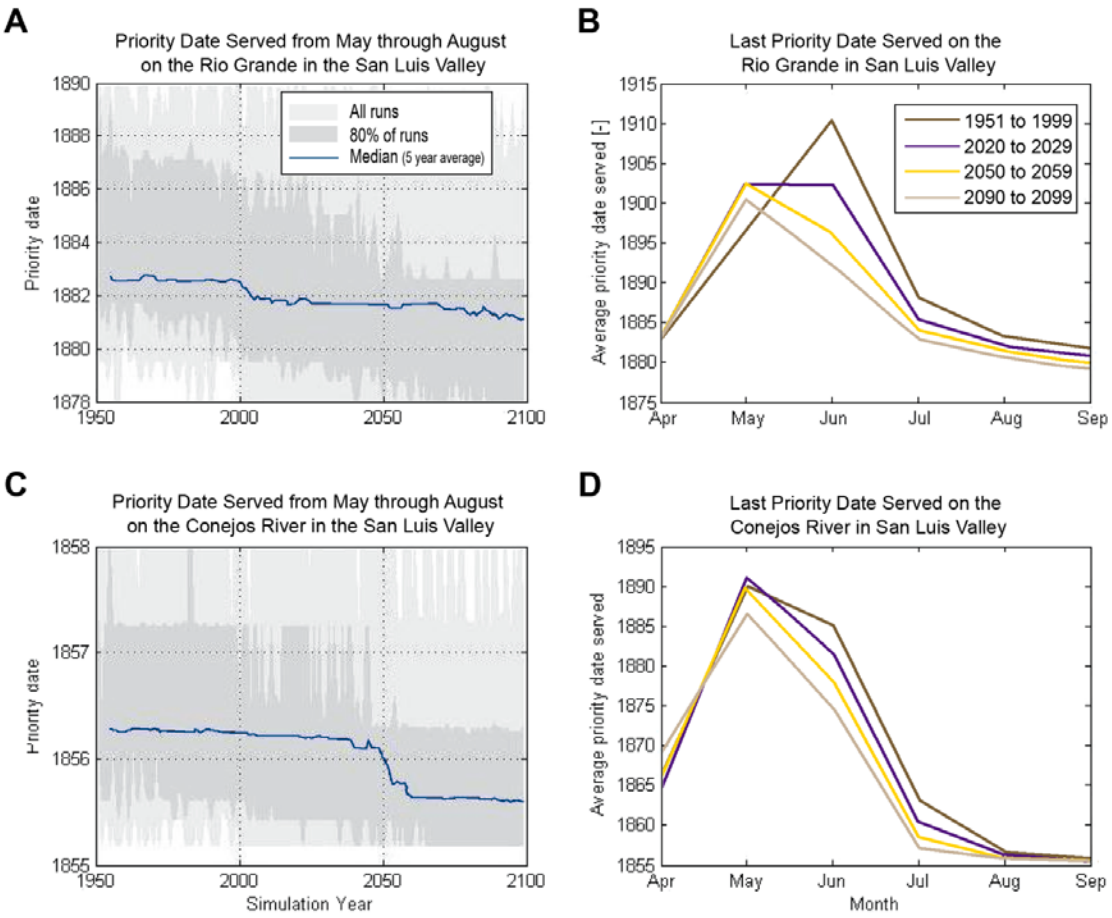

Figure 30.—Priority dates of water rights that would be fully served in the summer from the Rio Grande and Conejos River in the San Luis Valley (Panels A and C) and associated average monthly priority dates served (Panels B and D).

- **Water rights would be served earlier in the irrigation season.** On both rivers, fewer rights are satisfied during the months of June through September over time. On the Rio Grande, there is no significant change in the average right served in April, and more water rights are served in May, due to an earlier runoff peak (runoff peaks in May rather than June). On the Conejos River, more rights are served in April, and after an initial increase in rights served in May during the 2020s, fewer water rights are served in all months from May through September as the simulations progress.

4.3.3 New Mexico Water Delivery

4.3.3.1 Otowi Gage

The Otowi gage is downstream of the confluence of the Rio Chama and Rio Grande and above Cochiti Reservoir (see Figure 3 for locations), and thus it is an important representation of total system inflows to New Mexico. The Otowi gage represents the official inflow point to the portion of New Mexico for which flows and downstream deliveries must be accounted under the Rio Grande Compact. Figure 31 provides the analysis results for the ensemble of simulations for projected future flows at Otowi gage.

Projections show that:

- **Flows passing Otowi Gage would decrease.** Median projections suggest that annual-average flows would decrease from around 1,400 cfs to around 1,000 cfs (29 percent) by the year 2100.

- **Timing of peak flows would not change significantly.** The average peak flows have historically occurred in May. Change in timing of peak flows in the Rio Grande headwaters (Figure 14) are masked by tributary inflows that do not show a change in peak timing (Figure 15), and the result is reduced relative flows in June, but there is no shift in the peak flow month at Otowi. Peak flows on the Chama and in the San Juan-Chama tributaries are largely captured by the series of reservoirs in the Chama system, and thus have a reduced effect on the timing of the peak seen at Otowi.

  The November peak is a result of non-irrigation season releases from Chama system reservoirs. March and April flows are larger than any historically observed in those months between 2 and 3 percent of the time by the 2090s.

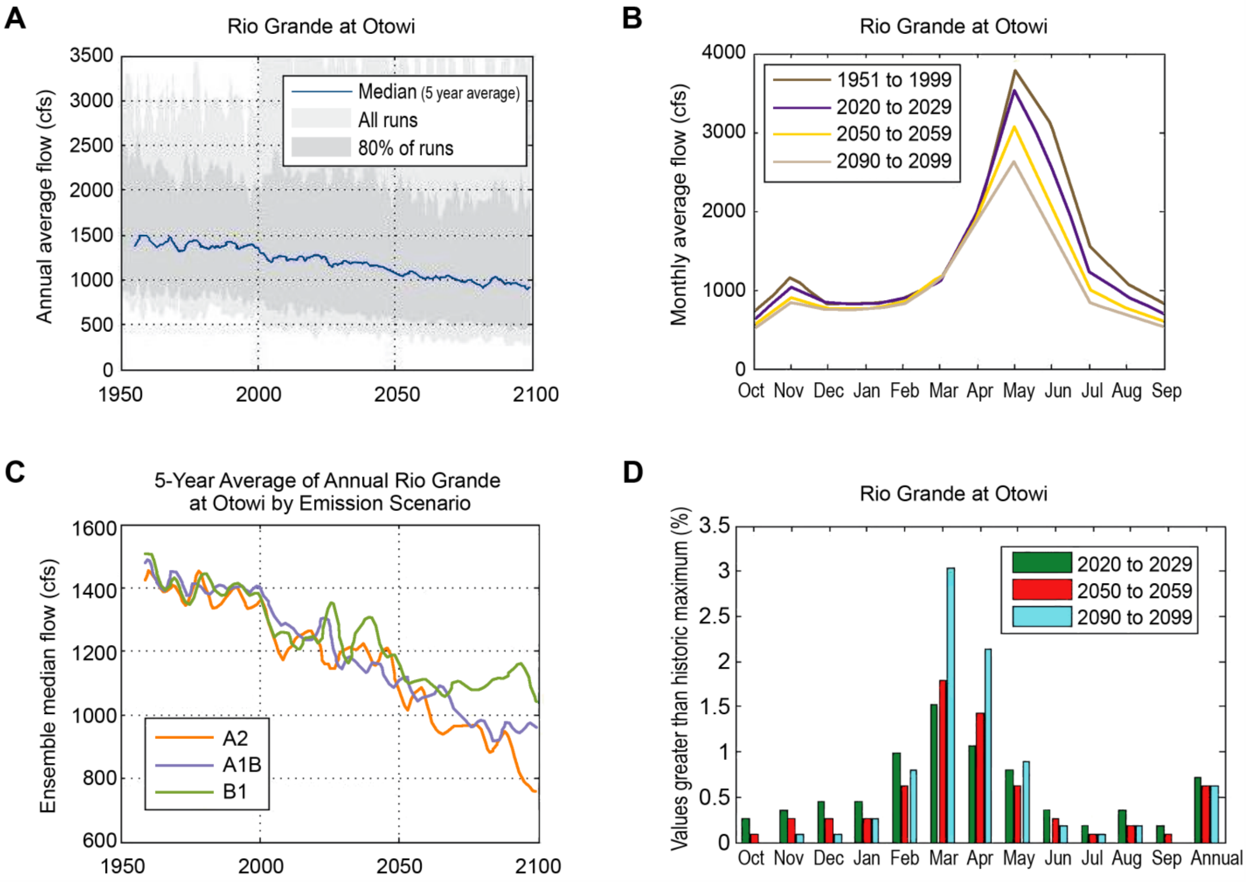

Figure 31.—Projected Rio Grande flows at Otowi gage.

4.3.3.2 Central Avenue, Albuquerque

Figure 32 provides the analysis results for the ensemble of simulations for flows at Central Avenue in Albuquerque.

Projections show that:

- **Flows at the Central Avenue Gage would decrease.** The flows at Central Avenue are projected to decrease by 36 percent, from an annual average of approximately 1,100 cfs during the historic period (1950 through 1999) to less than 700 cfs by the 2090s. The shape of the hydrograph mirrors that seen at the Otowi gage, with May through August flows significantly reduced, but without changes in the timing of the average peak monthly flow.

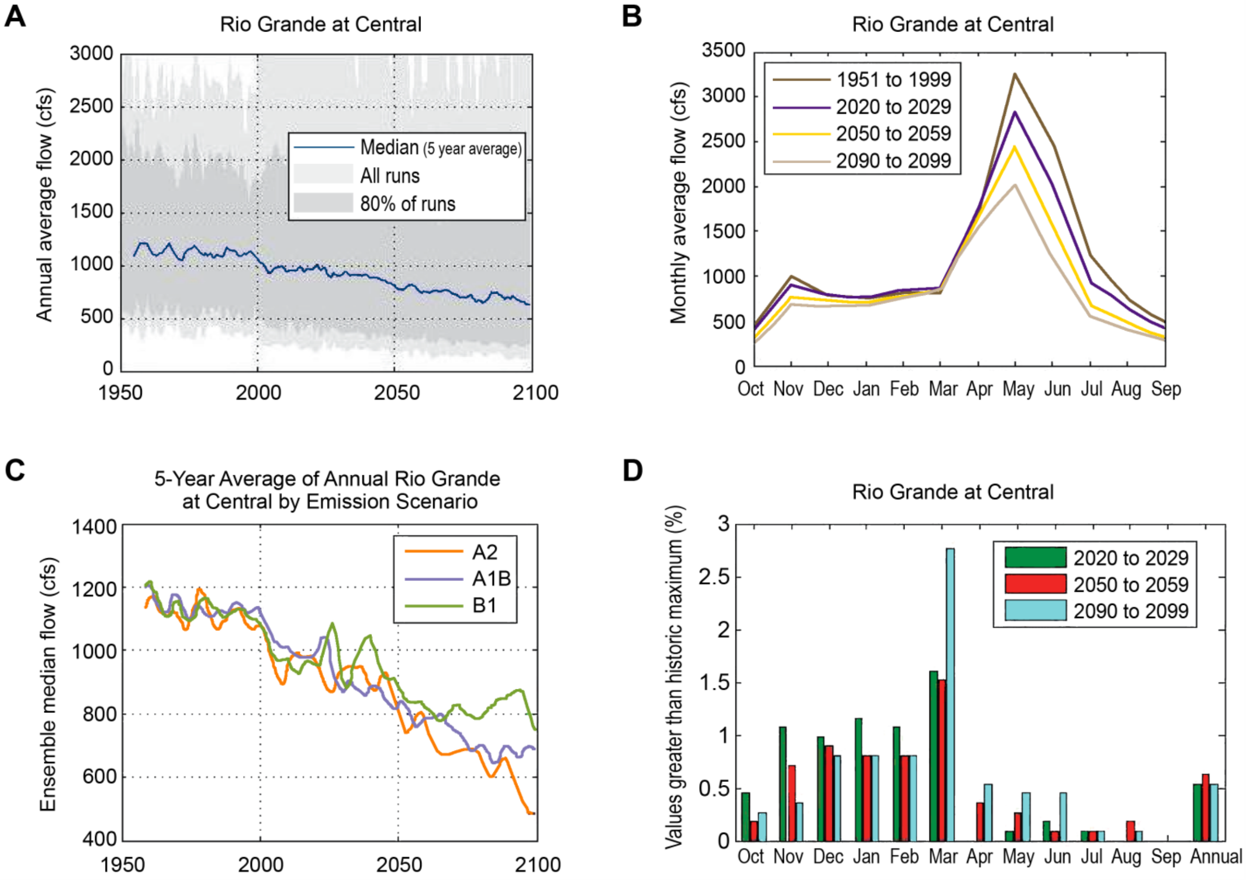

Figure 32.—Projected Rio Grande flows at Central Avenue in Albuquerque.

4.3.3.3 Elephant Butte and Caballo Reservoirs

Elephant Butte and Caballo reservoirs are located close together at the downstream end of the URGIA study area. Inflows to these reservoirs reflect both changes in the inflows to the Upper Rio Grande Basin and the changes in demand within the basin upstream of these reservoirs. Figure 33 through Figure 35 provide the analysis results for the ensemble of simulations for these inflows.

Figure 33 shows projected inflows into Elephant Butte Reservoir under both the Base Case Scenario, in which current operations are assumed, as well as an additional Compact Compliance Scenario, in which it is assumed that New Mexico takes management actions, for example reducing agricultural area, to assure compliance under the Rio Grande Compact.

In Figure 34, the differences between inflows to Elephant Butte under the Base Case Scenario and the Compact Compliance Scenario are shown, in terms of trends over time of the median and range (Figure 32 Panels A and C), monthly patterns at specified time periods in the future, and broken down by emission scenario. The differences between these two scenarios are not large on an annual basis, but they represent the annual deficit within New Mexico upstream of these reservoirs. If management actions are not taken to mitigate these shortages, they would build up over time.

Figure 35 shows simulated releases out of Caballo Reservoir at the downstream boundary of the study area. The shape of the average hydrograph is based on a typical irrigation schedule for Reclamation’s Rio Grande Project, the irrigation project that operates downstream of Elephant Butte and Caballo Reservoirs (and is outside of the study area for the URGIA). The average hydrograph includes a pulse of water in March to start the irrigation season, and then releases peaking in June to serve agricultural demand. Our modeling assumes that climate change does not change the shape of this irrigation schedule, although it reduces the overall quantity of available water.

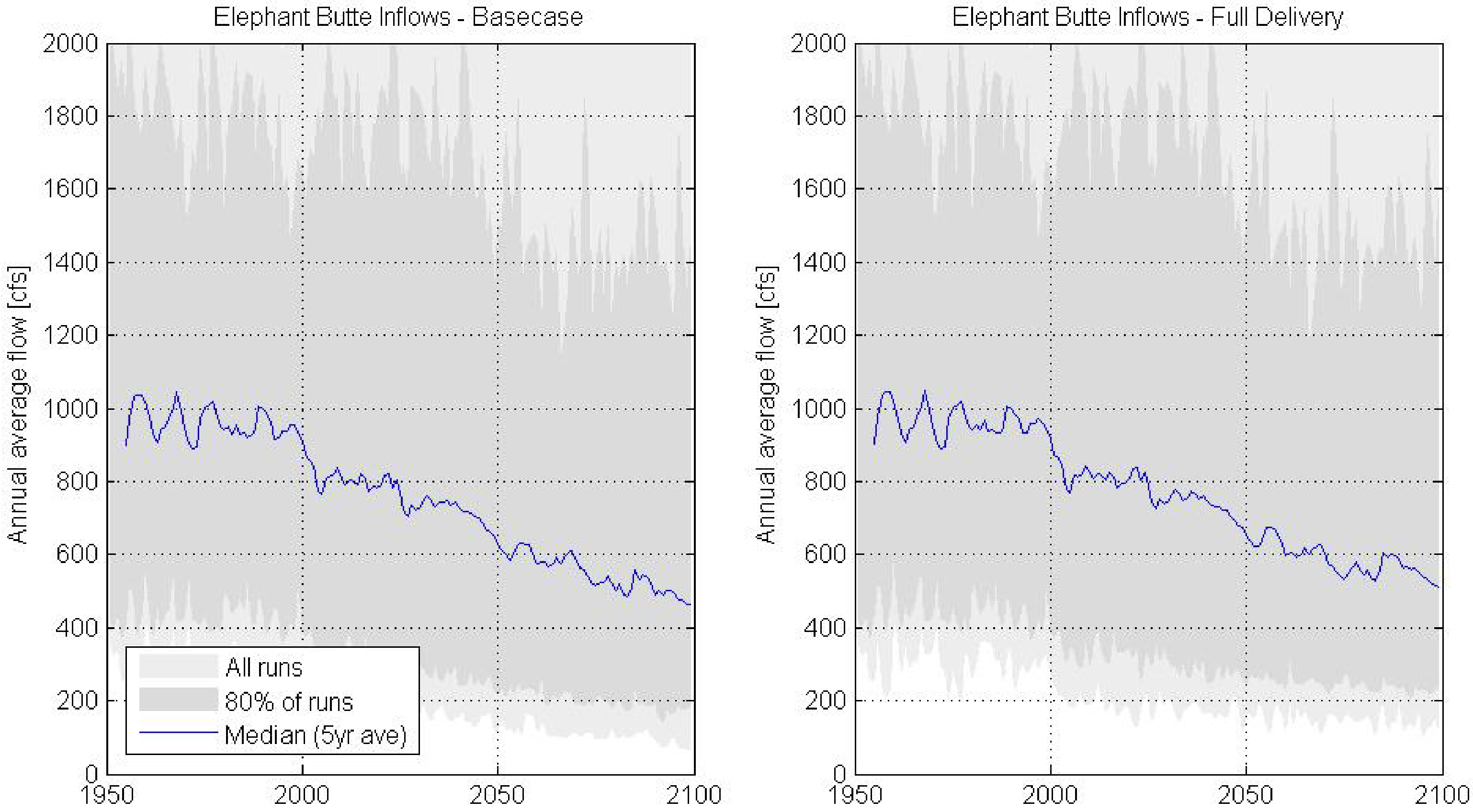

Figure 33.—Projected inflows to Elephant Butte under the Base-Case and Compact Compliance Scenarios.

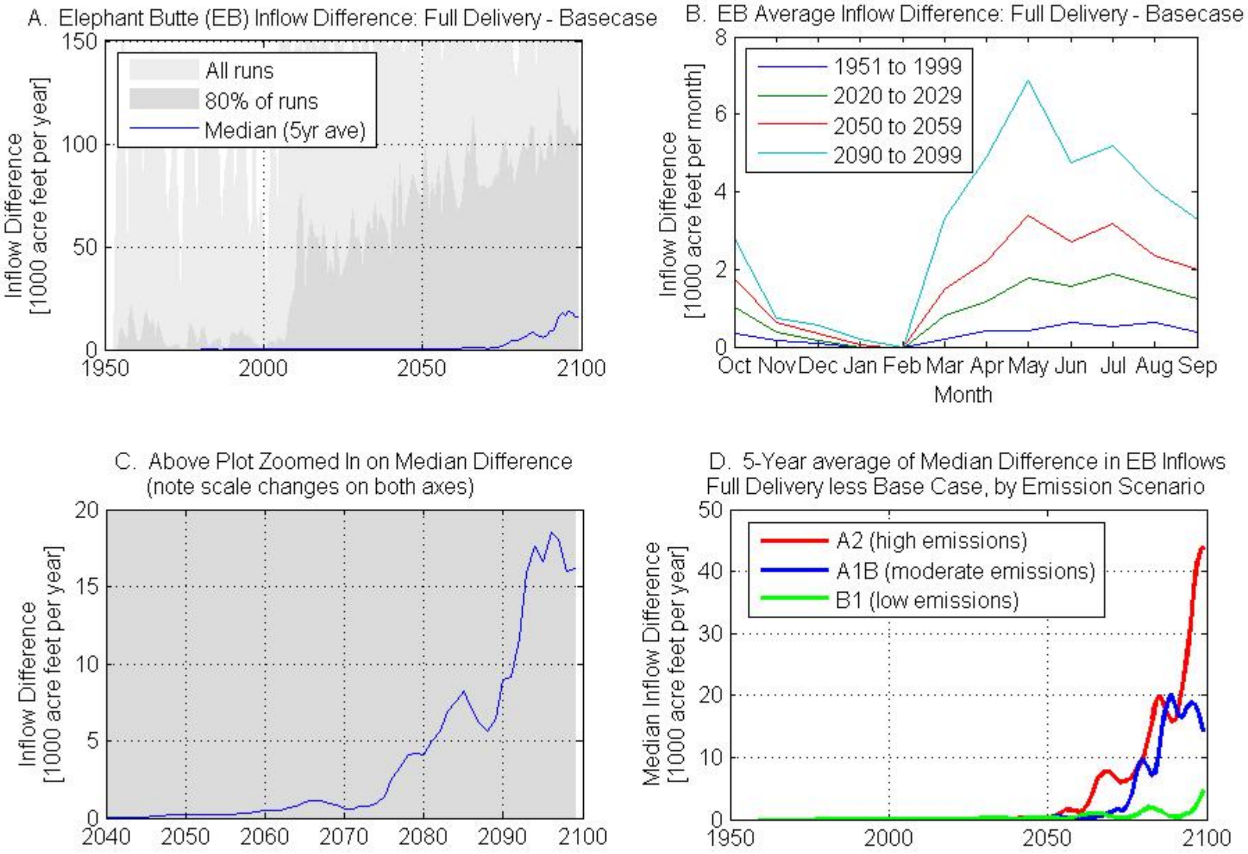

Figure 34.—Differences in inflows to Elephant Butte Reservoir under the Base Case and Compact Compliance Scenarios.

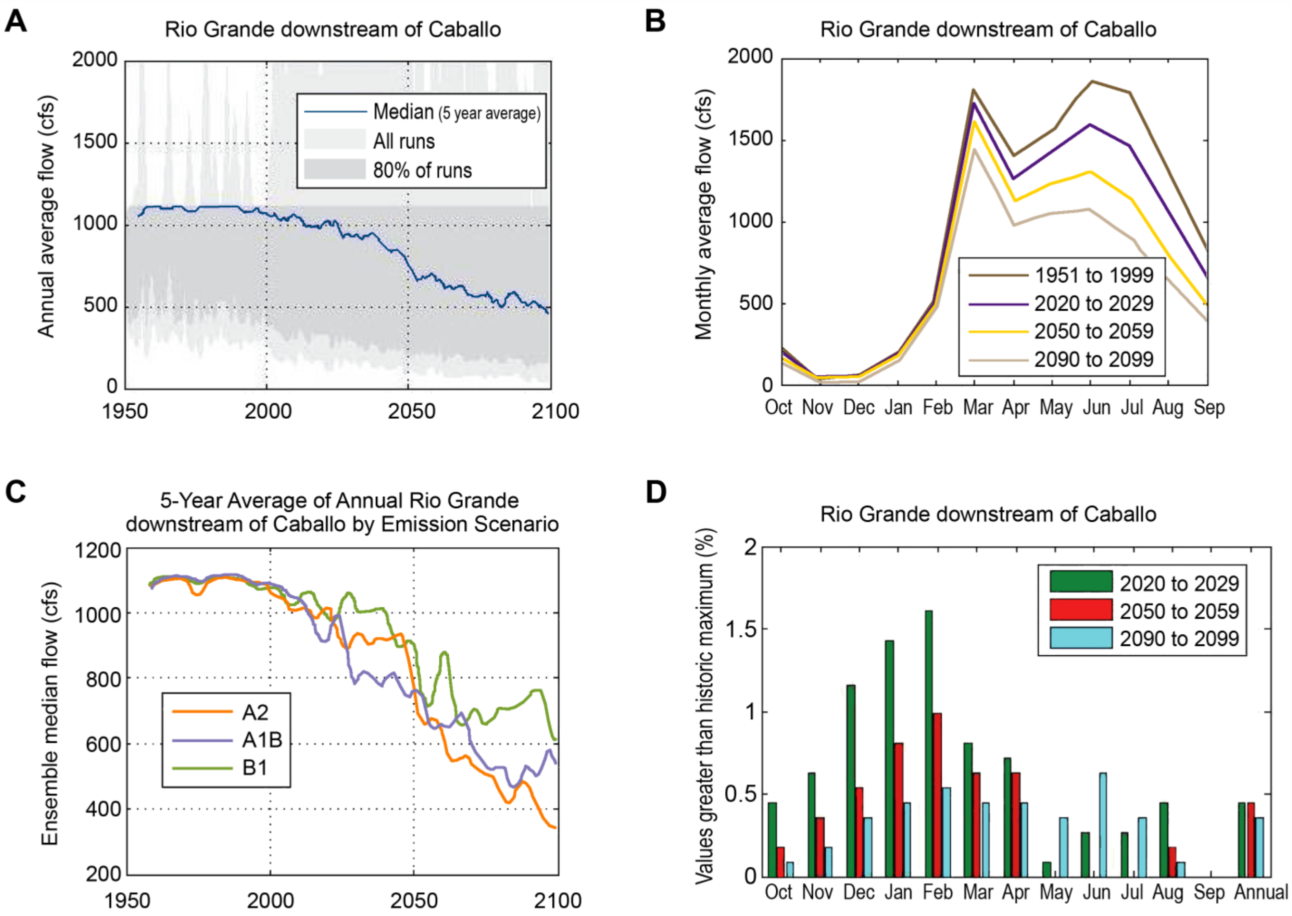

Figure 35.—Projected releases into the Rio Grande Project below Caballo Reservoir, at the downstream end of the study area.

Projections show that:

- **Flows would become more variable.** Early in the simulations, flows from December through April are most likely to exceed flows documented in historic records, while later in the simulations, the likelihood of a new record monthly high is distributed throughout the year, including during summer months. Because this summer-month variability was not as noticeable at Central Avenue (Figure 32), it seems that the summer (monsoonal) rains into tributaries downstream of Central Avenue, namely Tijeras Arroyo and the Rio Puerco, are responsible for this apparent gain in variability.

- **Releases would decrease.** The projections show a dramatic drop in average releases from Caballo Reservoir for the Rio Grande Project from 1,100 cfs, which is a full release from 1950 through 1999, down to a projected average annual release of 500 cfs at the end of this century (a 55 percent decrease). This decrease is associated with the Base Case Scenario. The Compact Compliance Scenario would experience a slightly smaller decrease.

4.3.4 New Mexico Water Consumption Under the Base Case Scenario

Model simulations describe the impacts of climate change on water delivery and demand, based on current development and land-use conditions.

Water demands are the optimum requirements, whereas consumption reflects the amount of water actually available. The largest categories of water demands and consumption in the Upper Rio Grande Basin are:

- **Irrigated agricultural ET** (i.e., a combination of evaporation and water use by plants). Demand rate calculations were based on potential evapotranspiration, (i.e., the maximum amount of water the vegetation could consume under ideal conditions). In central New Mexico, this demand is not fully met on average, even without water scarcity, due to operational inefficiencies. On a per-unit area basis, the agricultural consumptive demands are lower than any of the other demands.

- **Riparian vegetation ET.** Demand rates are calculated in the same manner as irrigated agricultural ET demand rates. The potential evapotranspiration for riparian vegetation demand rates are only met when groundwater levels are sufficiently high to allow optimal water uptake.

- **Municipal and industrial (M&I) consumption.** Demand rates are calculated using an outdoor vegetation ET, as other water demands are assumed to return to the system.

- **Reservoir evaporation**. The reservoir areas vary through time, and thus the volume of reservoir evaporation masks the rising trend in evaporation rates. Therefore, the demand rates for reservoir evaporation were based on reservoir storage estimates rather than with other factors such as temperature.

Demands for ET are shown as rates, which must be multiplied by irrigated agricultural area, riparian vegetation area, or the representative outdoor use area for M&I consumption. Figure 36 shows the maximum (or in other words, the potential) consumptive use demands for these demand types and represent the maximum amount of water that would be consumed under ideal conditions. It is recognized that these rates may not be achievable, even at current levels of water availability, but they do provide perspective on the total projected demand.

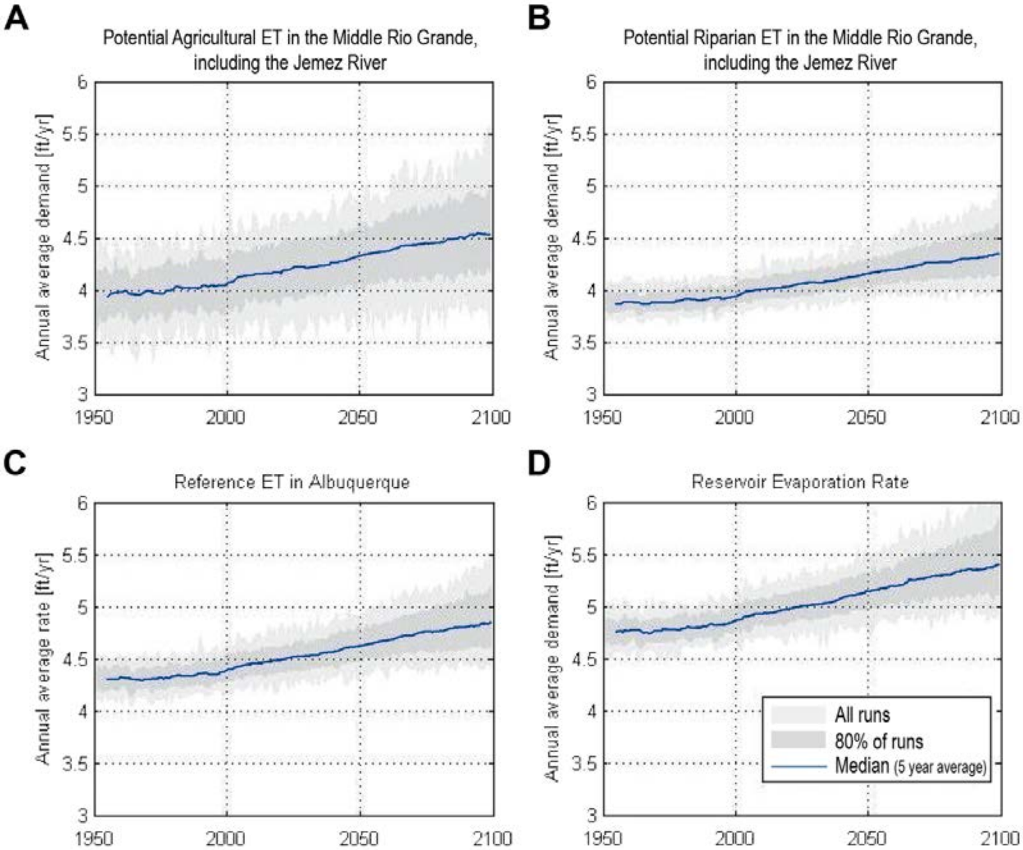

Figure 36.—Model-projected agricultural, riparian, M&I, and reservoir evaporation demand rates under the Base Case Scenario.

The demands shown in Figure 36 are spatially averaged for agricultural and riparian potential ET (Panels A and B) (in other words, the ET is multiplied over the irrigated agricultural area or the riparian vegetation area, respectively). Reference ET (i.e., the representative ET for the outdoor use area used in the M&I demand calculations) is shown in Panel C as the Albuquerque area Reference ET, as this is where most of the population is located. Panel D shows the open-water evaporation rates for all reservoirs.

Each of these parameters changes are due to climate change, even without further agricultural or M&I development. ET-related consumptive demands, including demand for irrigated agriculture, riparian vegetation, and municipal and industrial outdoor use in New Mexico, are expected to rise with rising temperatures (Figure 36). The actual consumptive use by each of these sectors will depend on the available supply and the ability of the sector to take advantage of that supply.

Results for each sector are discussed in the following subsections. For agricultural and riparian vegetation, the potential consumptive use may not be fully met even with abundant supply due to operational inefficiencies or suboptimal groundwater levels, respectively. In the operational model runs for this study, the municipal and industrial consumption demand is always fully met regardless of surface water supply, due to groundwater pumping.

Overall our analysis found that, while the combination of decreased supply and increased demand threatens the system, the system responds to the decreased supply with slightly decreased consumption. Although ET demands rise with rising temperatures, the sum of consumption associated with these demands actually decreases as supplies drop. The reservoir evaporation is the largest decrease and more than offsets increases in agricultural ET and municipal consumptive use, while riparian ET also decreases due to supply limitations, despite increased potential consumption.

Section 4.3.5 discusses these changes in water consumption under the Rio Grande Compact.

4.3.4.1 Agricultural Consumption

Agricultural consumption depends on the potential demand rate for the irrigated area, and the available supply (Figure 36). Figure 37 provides the analysis results for the ensemble of simulations for agricultural consumption. This analysis considers climate inputs only and does not change the amount of irrigated areas (see Section 3.3). However, consumption will drop if supply is insufficient to meet demand. Operational inefficiencies may also prevent the potential consumptive use from being fully met, even with abundant supply.

Projections show that:

- **Agricultural ET demands increase.** Figure 37 shows that, on average, agricultural ET losses rise by approximately 5 percent during the simulations, which is less than would be expected based on the change in potential ET (Figure 37, Panel D). This dampening from demand to actual use is a result of insufficient supply, which is also evident in a prominent lower envelope of low actual crop consumption (Figure 37, Panel A). ET appears to increase in the early part of the irrigation season (March through June), and decrease in the latter part of the season, Figure 37 Panel B), again due to supply limitations later in the year. Years with sufficient supply are rare, but in those years agricultural consumption is higher (by almost 15 percent) than any observed in the historic period (Figure 37, Panel D).

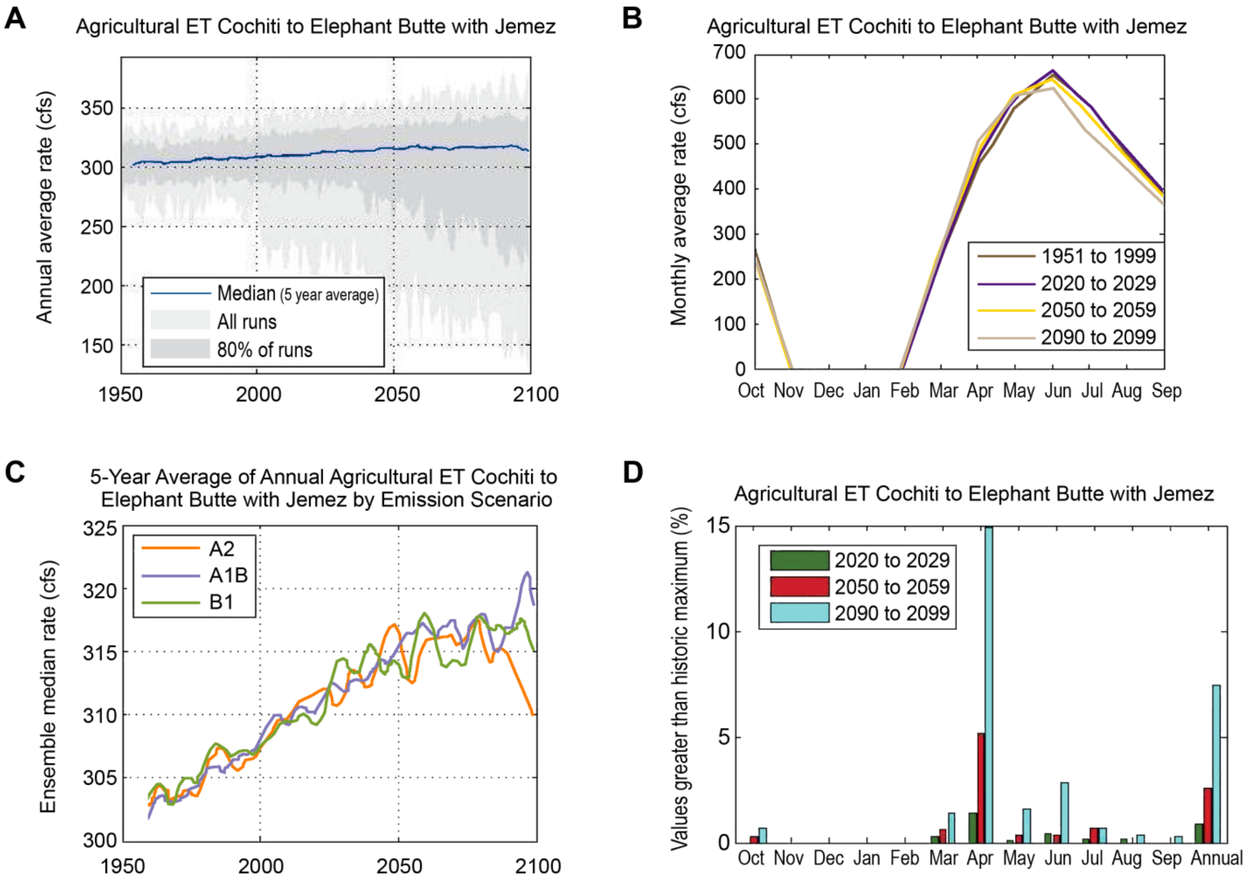

Figure 37.—Total projected crop consumption between Cochiti and Elephant Butte Reservoirs, including the Jemez River valley.

4.3.4.2 Riparian Consumption

Riparian vegetation consumption depends on the potential demand rate (Figure 36), the riparian area, and the available supply to the trees. Figure 38 provides the analysis results for the ensemble of simulations for riparian consumption.

Projections show that:

- **Riparian ET demands would be reduced as a result of declining groundwater levels.** As this analysis considered only climate-change impacts, the riparian area was held constant throughout the analysis (see Section 3.3.). However, riparian consumption varies—depending on groundwater levels, which respond, in in a delayed manner, to reductions in surface water recharge of the shallow groundwater. Figure 38 shows that, on average, riparian ET decreases slightly through the simulations. This is a result of declining shallow groundwater levels, which result in reduced actual ET (the amount of water actually evaporated or transpired) despite increased potential ET (the amount of water that could have been evaporated or transpired if there were sufficient water to meet demand). Figure 38, Panel D shows that, toward the end of the century in the scenario that was modeled, most of the actual consumption would occur in April and May, when water is available. Although potential ET would continue to be high in June through September, water would not be available to meet that demand. The breakdown by emission scenarios in Figure 38, Panel C shows that riparian ET is greater under the less severe emission scenarios because more water would be available to meet demand.

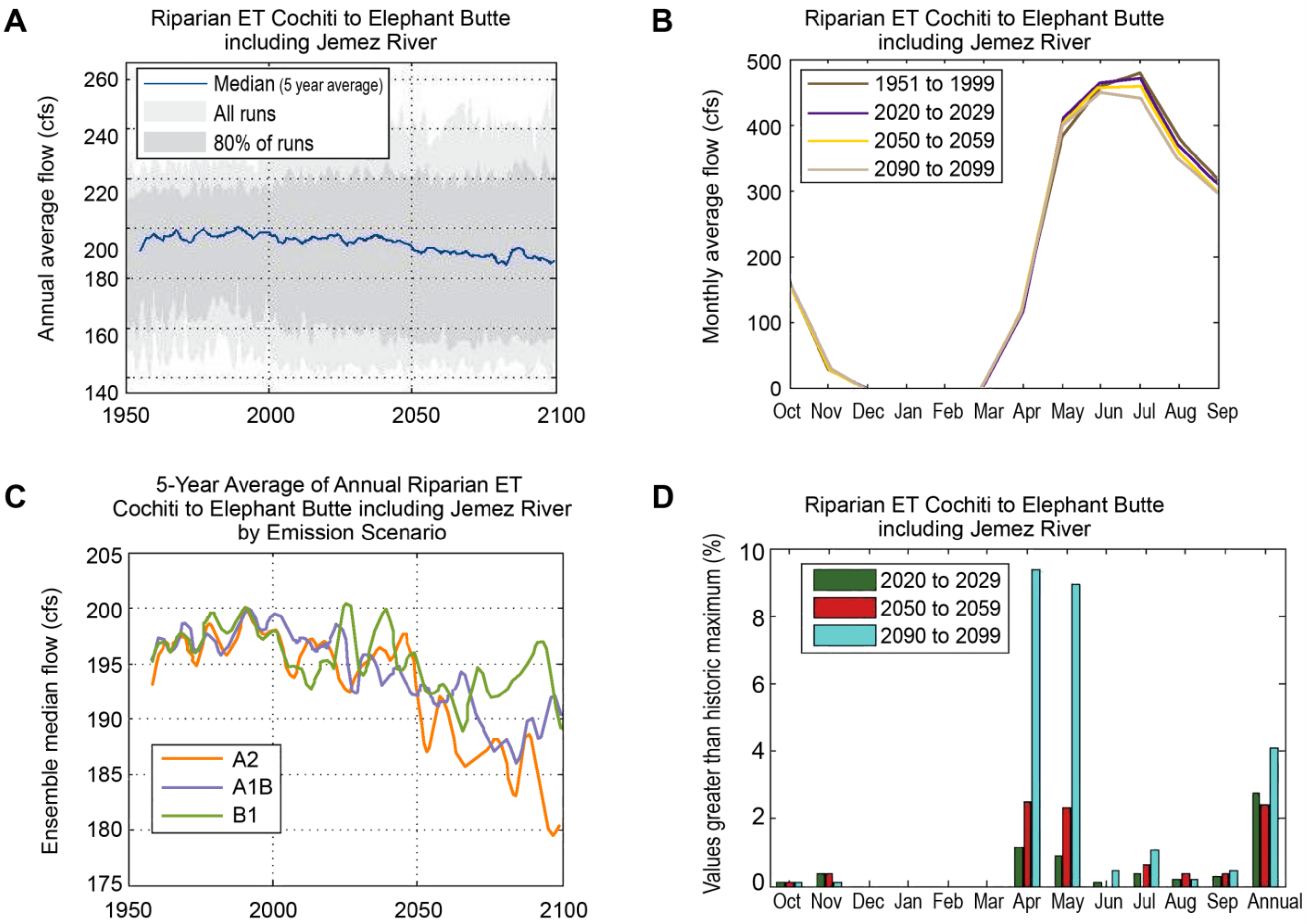

Figure 38.—Simulated riparian evapotranspiration from Cochiti to Elephant Butte Reservoirs, including the Jemez River valley.

4.3.4.3 Municipal Consumption

For the URGIA analysis, we assumed that water used by cities would return to the system if it is used indoors, and water would be lost to the atmosphere if it is used outdoors. The change in consumptive (outdoor) use by the municipal sector in response to climate change is small compared to the other three types of consumptive uses discussed here, since the urban area for which the water is used is small relative to the agricultural area. It is important to remember that population levels are held constant throughout the model runs. So, although population growth could drive up municipal consumption, the URGIA analysis only considers increases in consumption associated with changes in temperature or precipitation.

Figure 39 provides the analysis results for the ensemble of simulations for consumptive municipal use for all cities included in the modeling for this study (Espanola, Los Alamos, Santa Fe, Bernalillo, Rio Rancho, Albuquerque, Los Lunas, Belen, Socorro, and Truth or Consequences). Generally, consumptive use for vegetation is the only outdoor water use allowed in municipalities. The increase in reference ET of about 10 percent (seen in Figure 36) translates directly to about the same percentage increase in consumptive (outdoor) municipal use. Total indoor use for these same cities is about 130 cfs and is invariant throughout the simulations.

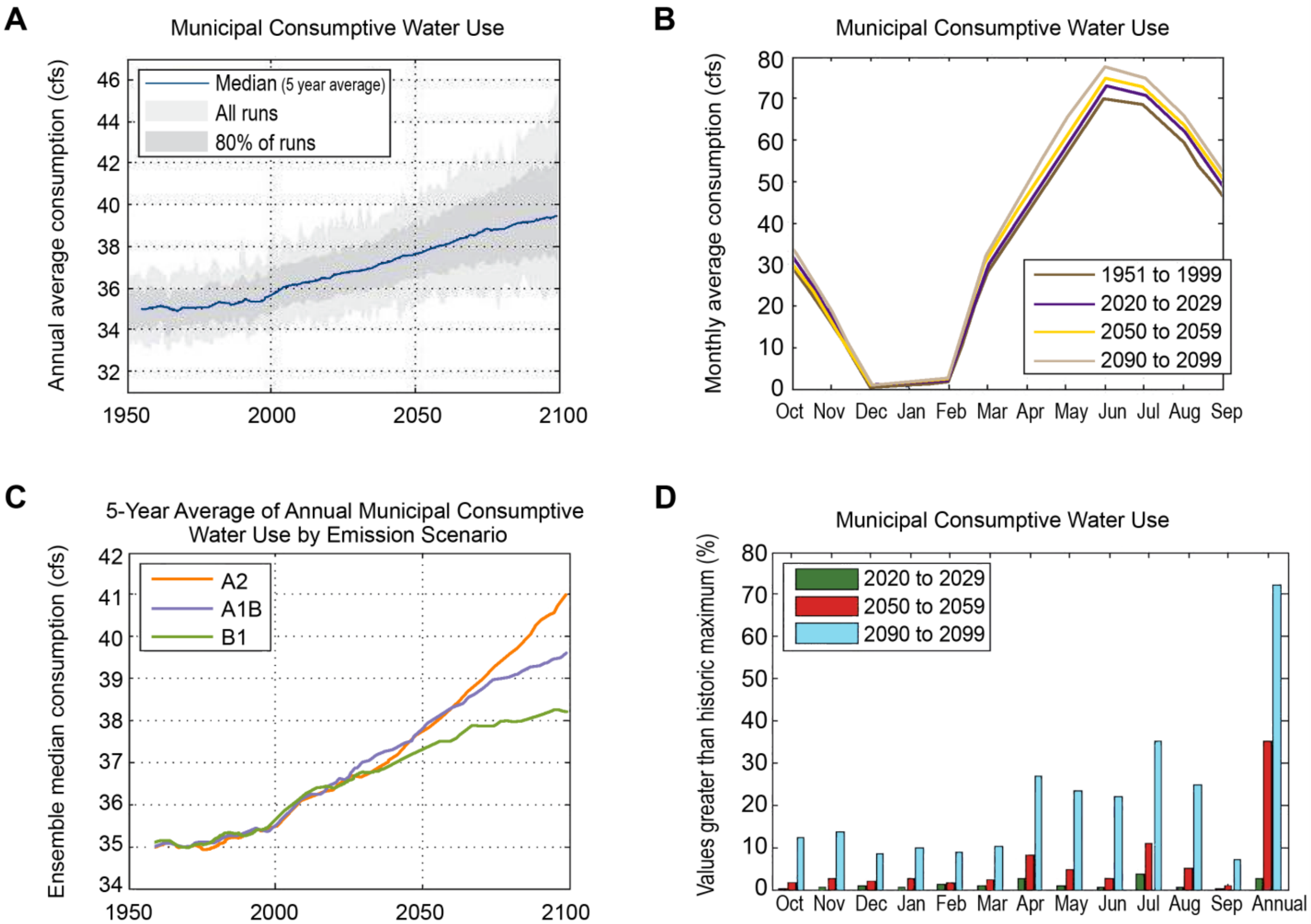

Figure 39.—Simulated municipal consumptive use.

4.3.4.4 Reservoir Evaporation

Figure 40 through Figure 42 provide the analysis results for the ensemble of simulations for projections of the volume of evaporation from New Mexico reservoirs. This volume drops by almost 50 percent in the projections due to reduced reservoir storage throughout the system (there is less water in the reservoirs that can be evaporated). This is a stabilizing feedback: as supply in the system increases, reservoir storage and reservoir evaporation volume rise, reducing available supply. On the other hand, as supply decreases, the volume of water evaporated from the reservoir also decreases, which feeds back to increase available supply in the system. Because of the stabilizing nature of this feedback, there is little variation in the volume of water evaporated between emission scenarios. Because of the rising evaporation rate, full reservoirs would lead to higher evaporation losses than have historically been observed, as is shown in the bottom right graph in Figure 40.

The change in reservoir evaporation depends to great degree on the storage change in the reservoir. Heron, El Vado, Elephant Butte, and Caballo reservoirs tend to lose storage during the simulations, and thus lose less water to reservoir evaporation as the simulations progress (Figure 42). Abiquiu, Cochiti, and Jemez reservoirs, on the other hand, don’t lose much storage on average during the runs and thus don’t experience a reduction in evaporative loss.

Figure 41 provides the analysis results for the ensemble of simulations for reservoir evaporation rates at four reservoirs that represent the geographical range of the Upper Rio Grande Basin:

- Heron Reservoir is in the northern part of New Mexico, close to El Vado Reservoir

- Abiquiu Lake is further south

- Cochiti Lake is further south than Abiquiu Lake and close to Jemez Canyon Reservoir

- Elephant Butte Reservoir is at the tail end of the Upper Rio Grande Basin and close to Caballo Reservoir

Note the difference in magnitude of evaporation rates as moving downstream. Jemez Canyon Reservoir is close to Cochiti Lake, and Caballo Reservoir is close to Elephant Butte Reservoir, so the evaporation rates at those reservoirs would be similar.

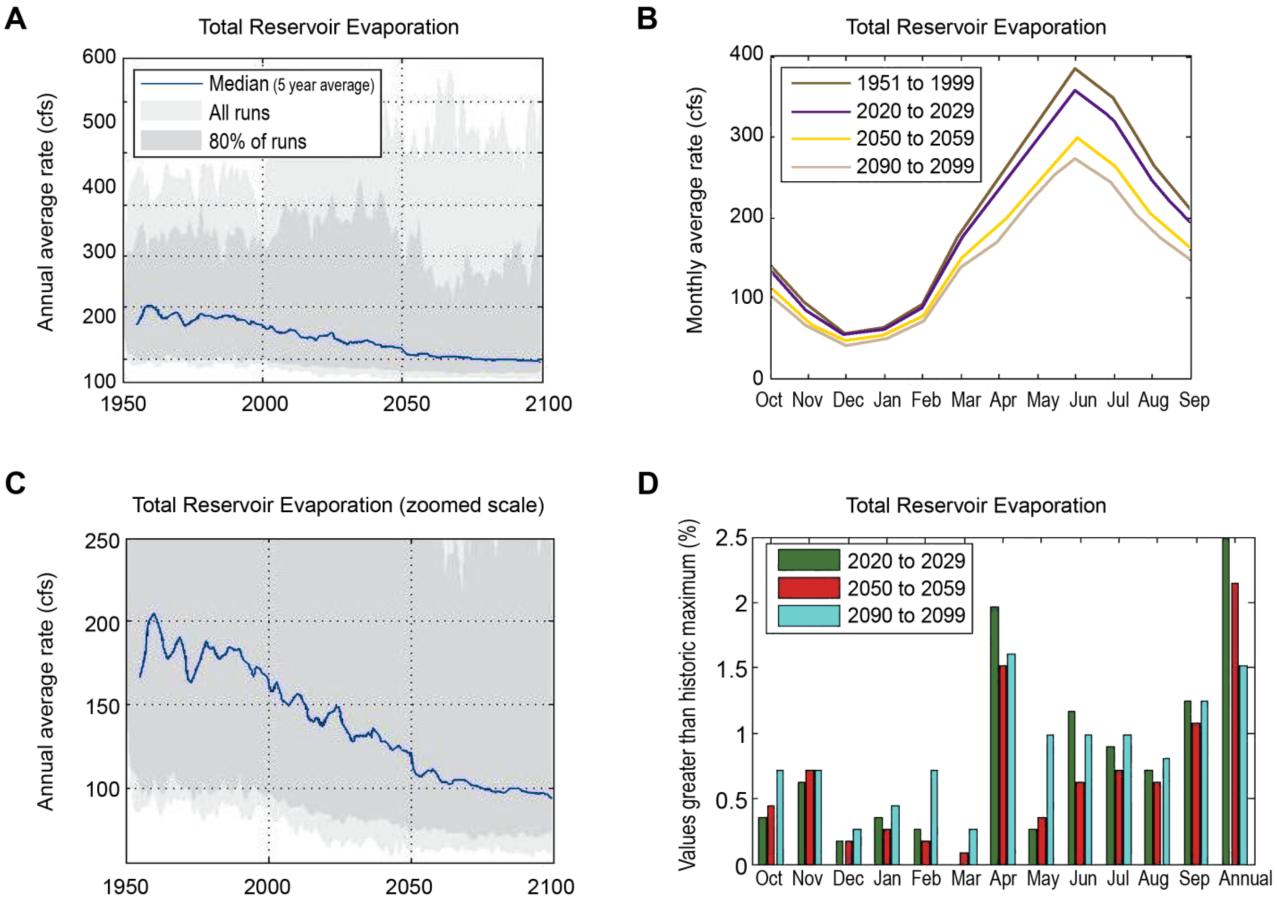

Figure 40.—Total projected evaporation from New Mexico reservoirs.

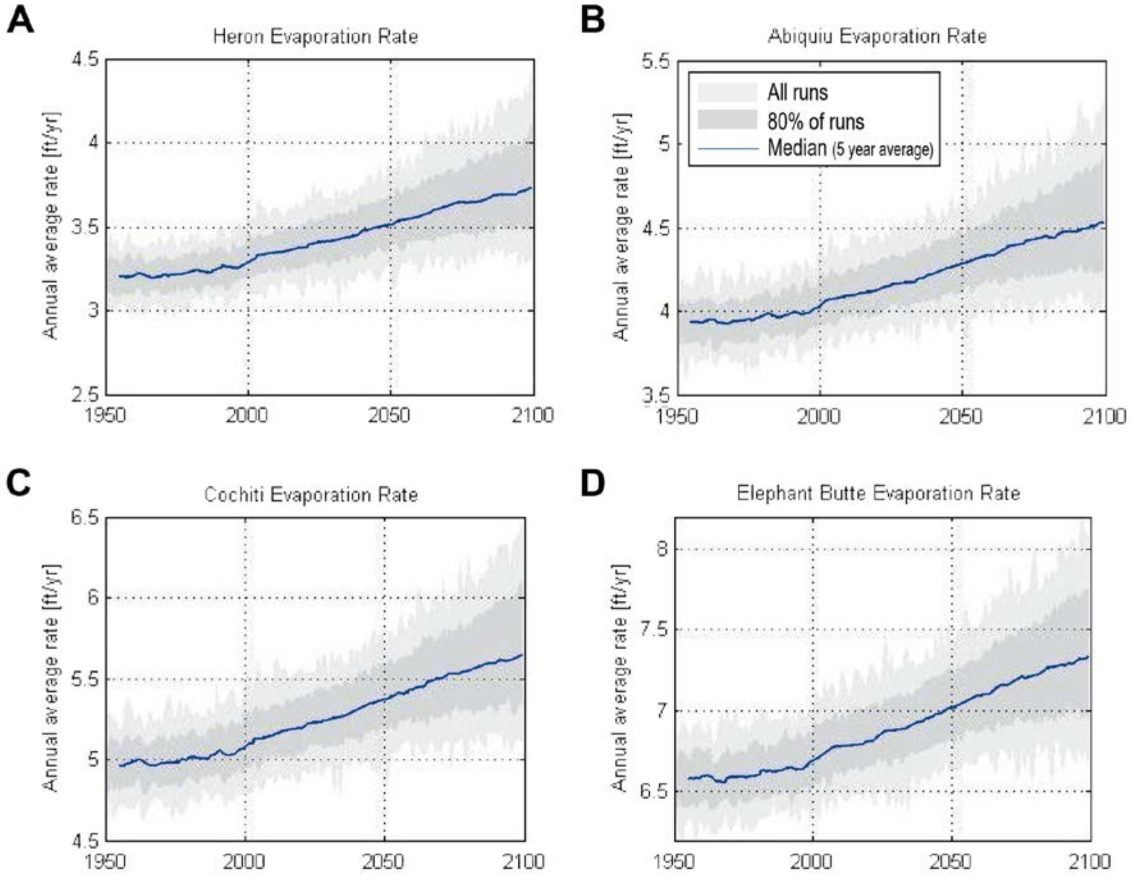

Figure 41.—Open-water evaporation rates at four reservoirs spread through the system from upstream (Panel A) to downstream (Panel D) in New Mexico. Note the different scales on the Y axes, though the range in each case is the same 2 feet per year.

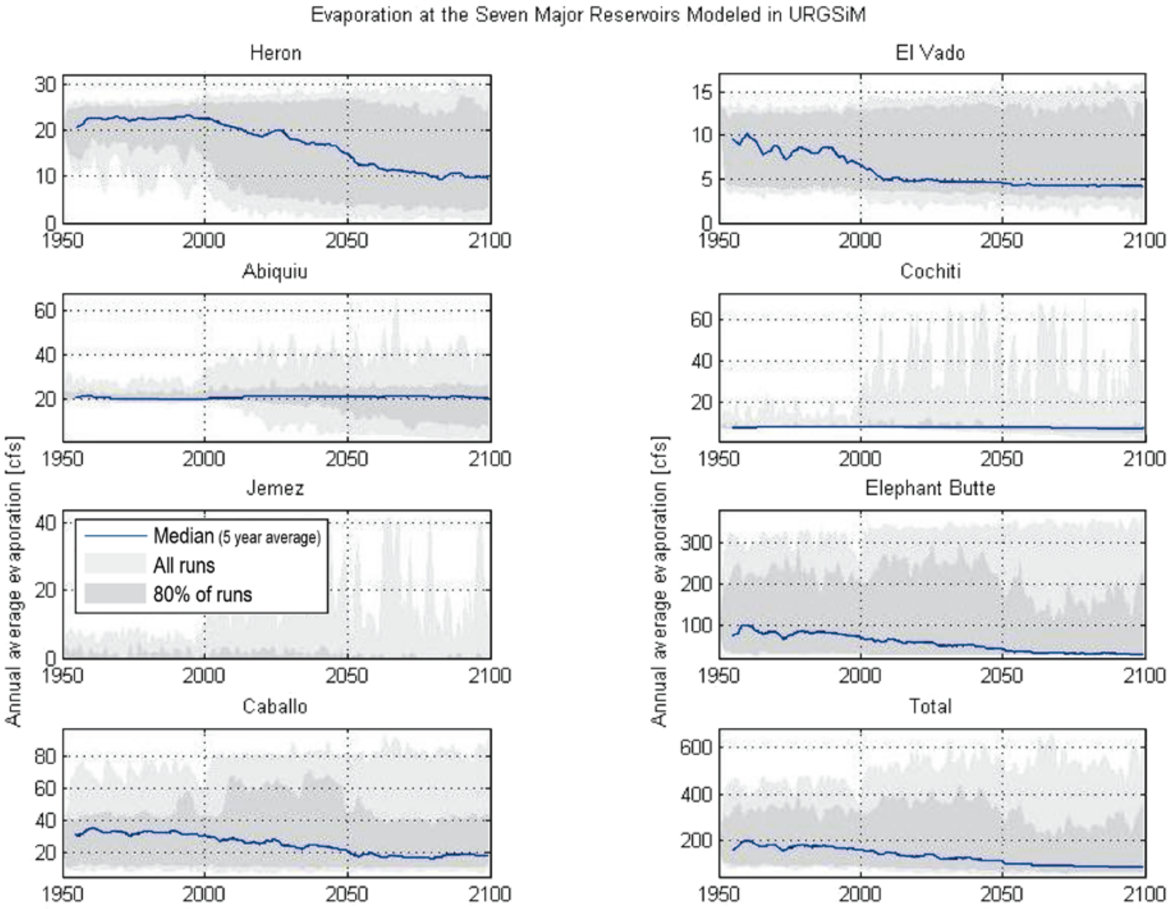

Figure 42.—Projected total reservoir evaporation at each of the seven major reservoirs in the Upper Rio Grande Basin in New Mexico.

4.3.5 Rio Grande Compact Compliance

This analysis focuses on potential hydrologic impacts of climate change alone on the Upper Rio Grande system with current water operations, infrastructure, and policies. In the Base Case Scenario, which forms the basis of most of the URGIA analyses, New Mexico does not have a specific policy for reacting to low deliveries by New Mexico to Elephant Butte Reservoir. New Mexico would, undoubtedly, take steps to assure Rio Grande Compact compliance under the conditions discussed in the previous sections of this chapter, through steps that might include reducing agricultural area or managing riparian vegetation. However, this study does not include any presumptions about what those steps would be.

A second set of model runs, in addition to the Base Case Scenario, were therefore made to determine downstream conditions with the assumption that New Mexico would take management actions to assure New Mexico's compliance under the Rio Grande Compact. This is referred to as the Compact Compliance Scenario. Results from these model runs for the ensemble of these simulations are shown in the following figures. Figure 43 shows the total storage, which highlights the dramatic increase in storage variability. Figure 44 and Figure 45 show Elephant Butte Reservoir storage under both the Base Case and Compact Compliance scenarios. Figure 46 through Figure 48 show the storage in the other six reservoirs under the Compact Compliance Scenario.

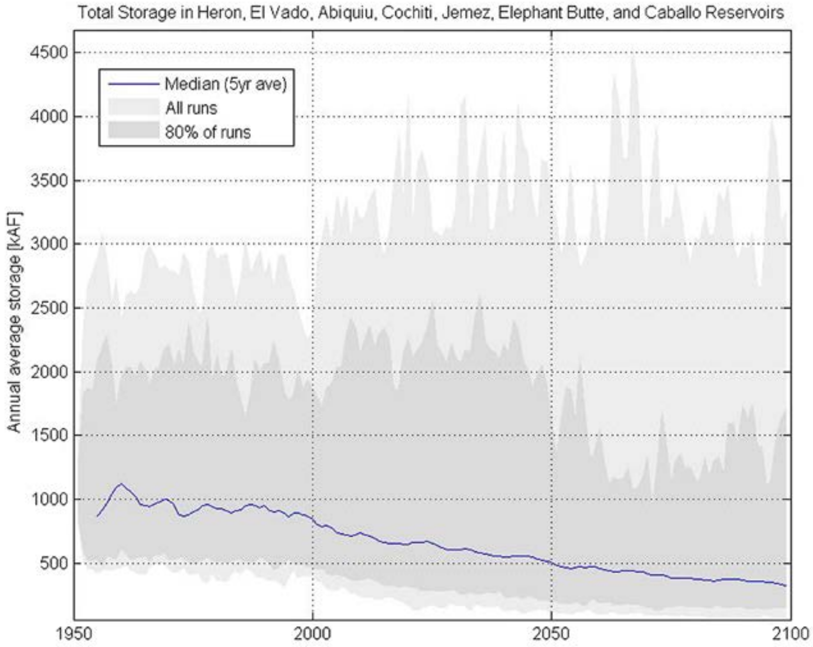

Figure 43.—Total reservoir storage under the Compact Compliance Scenario.

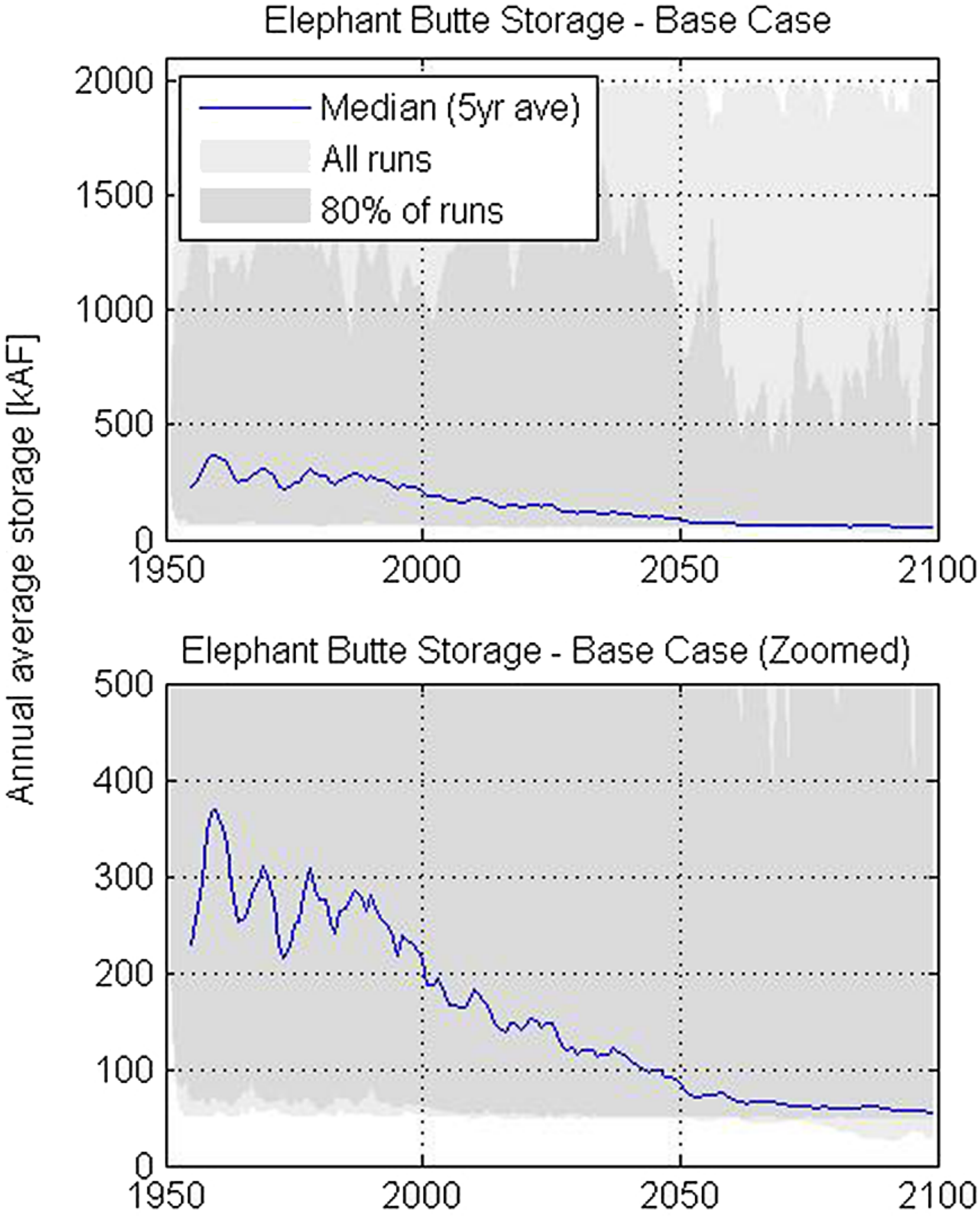

Figure 44.—Elephant Butte Reservoir Storage under the Base Case Scenario.

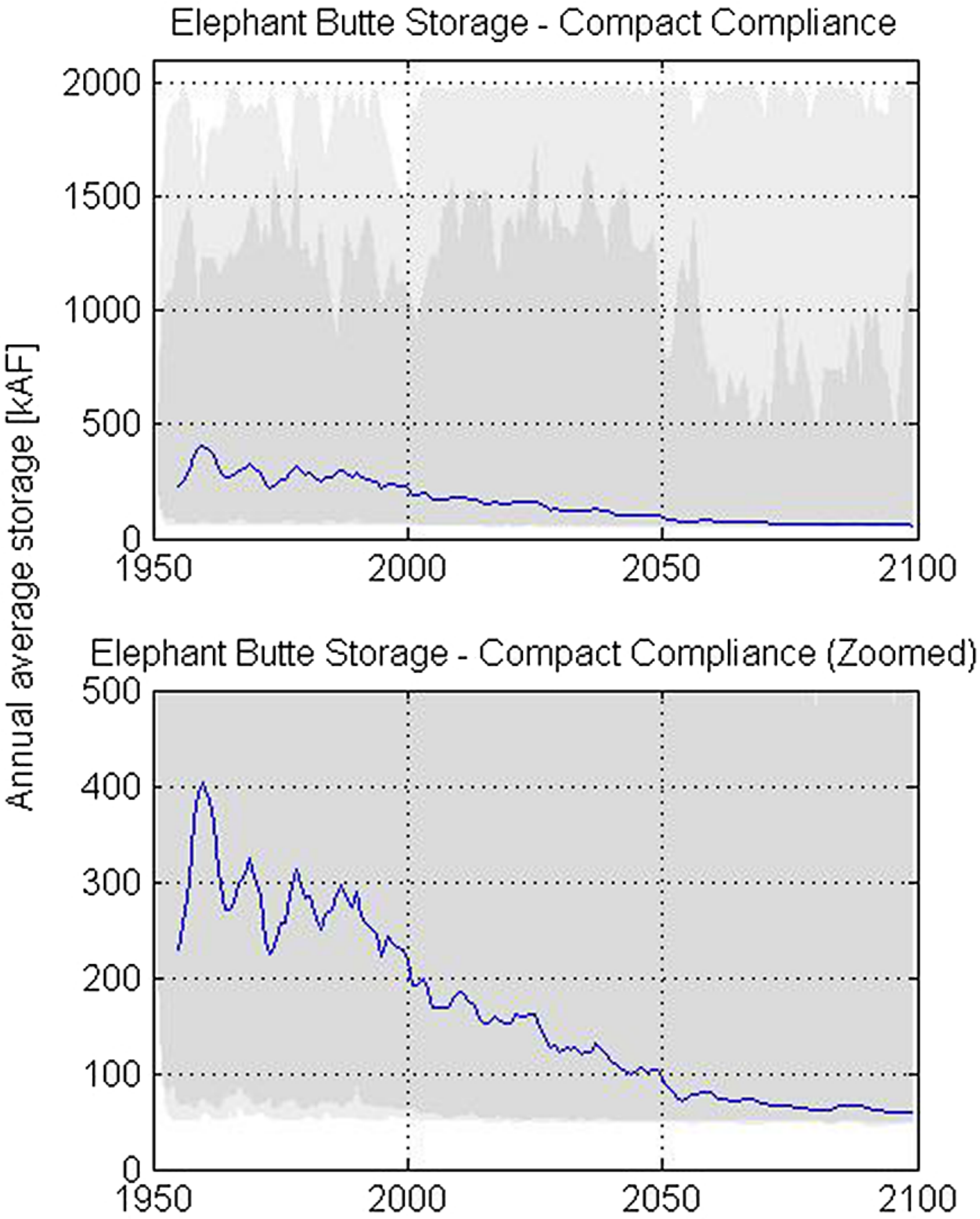

Figure 45.—Elephant Butte Reservoir storage under the Compact Compliance Scenario.

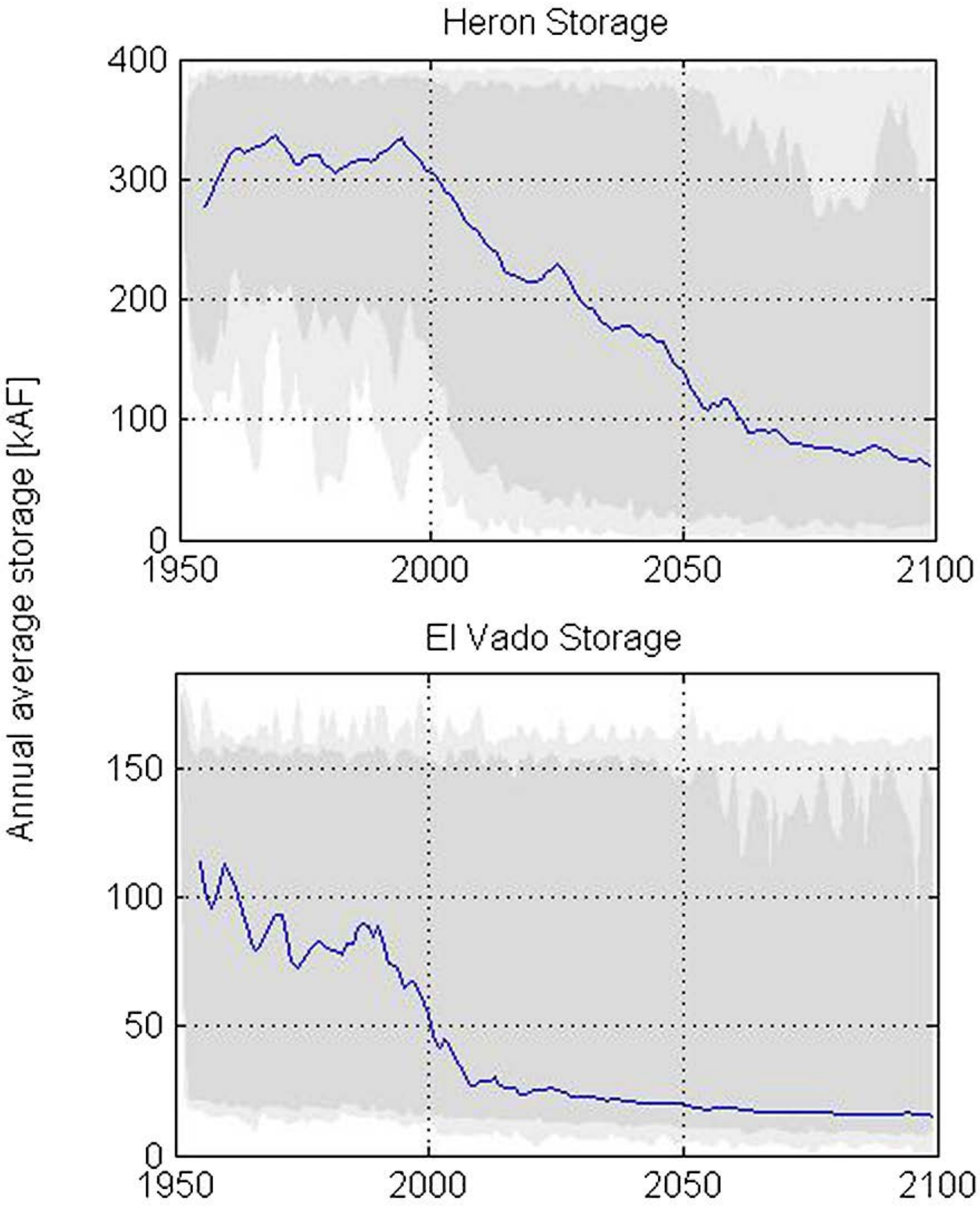

Figure 46.—Heron and El Vado reservoir storage under the Compact Compliance Scenario.

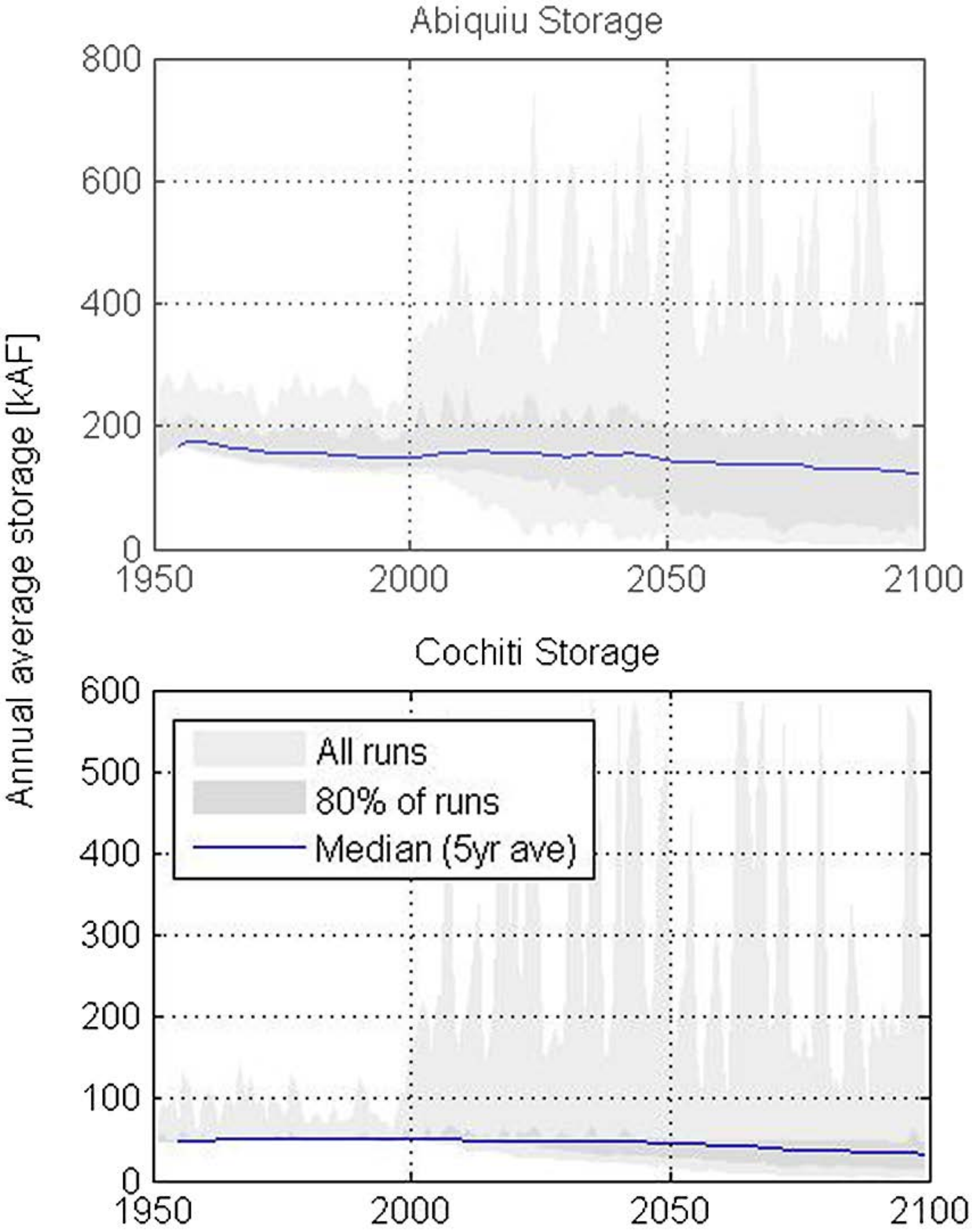

Figure 47.—Abiquiu and Cochiti reservoir storage under the Compact Compliance Scenario.

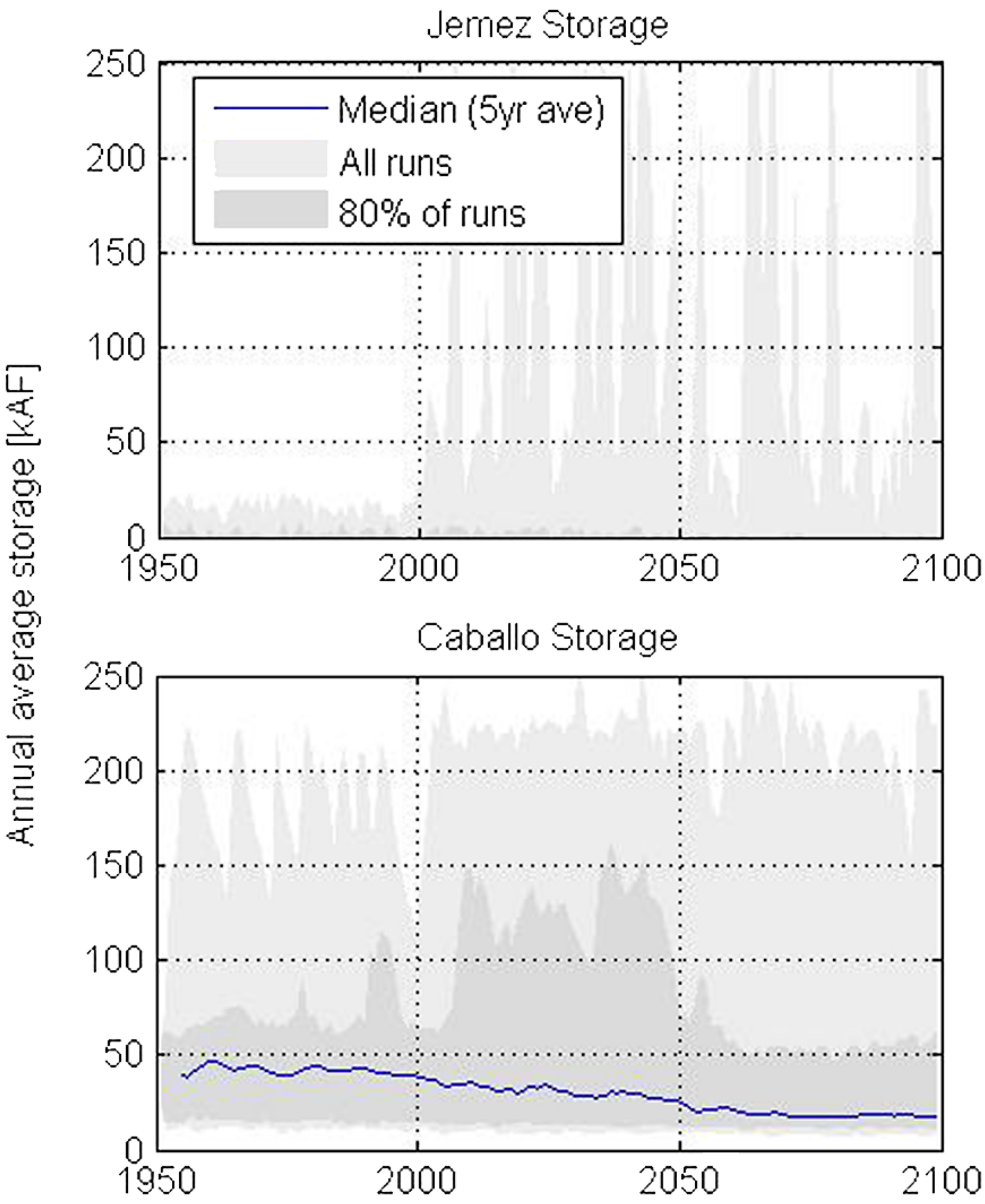

Figure 48.—Jemez and Caballo reservoir storage under the Compact Compliance Scenario.

5. Water Management Implications

The following sections summarize the implications of the hydrologic projections developed in the URGIA for management of the Upper Rio Grande system in terms of the parameters defined in the SWA.

- Section 5.1 discusses the water infrastructure and operations, including reservoir conditions and water delivery and hydropower generation impacts.
- Section 5.2. discusses flood control operations impacts.
- Section 5.3 discusses water quality impacts.
- Section 5.4 discusses fish and wildlife habitat, including environmental flow targets, ESA-listed species, and critical habitat impacts.
- Section 5.5 discusses flow and water-dependent ecological resiliency impacts.
- Section 5.6 discusses impacts to recreation.

5.1 Water and Power Infrastructure and Operations

5.1.1 Reservoir Conditions and Water Delivery

The reduced surface-water inflows to the Upper Rio Grande Basin, (Section 4.2) coupled with increased irrigated agricultural and riparian vegetation demands (Section 4.3), result in decreased reservoir storage throughout the system. Figure 49 provides the analysis results for the ensemble of simulations for projected reservoir storage for the seven major reservoirs in the Upper Rio Grande system, along with a projection of total reservoir storage in the system.

The reservoir levels shown in Figure 49 are associated with the Base Case Scenario, which assumes current operations and management actions. As described in Section 2.2.2, although New Mexico does not currently have a specific mechanism for assuring compliance under the Rio Grande Compact that can be simulated in an operations model, it is likely that New Mexico would make its deliveries, and the reservoir levels in Elephant Butte would be higher than shown in Figure 49.

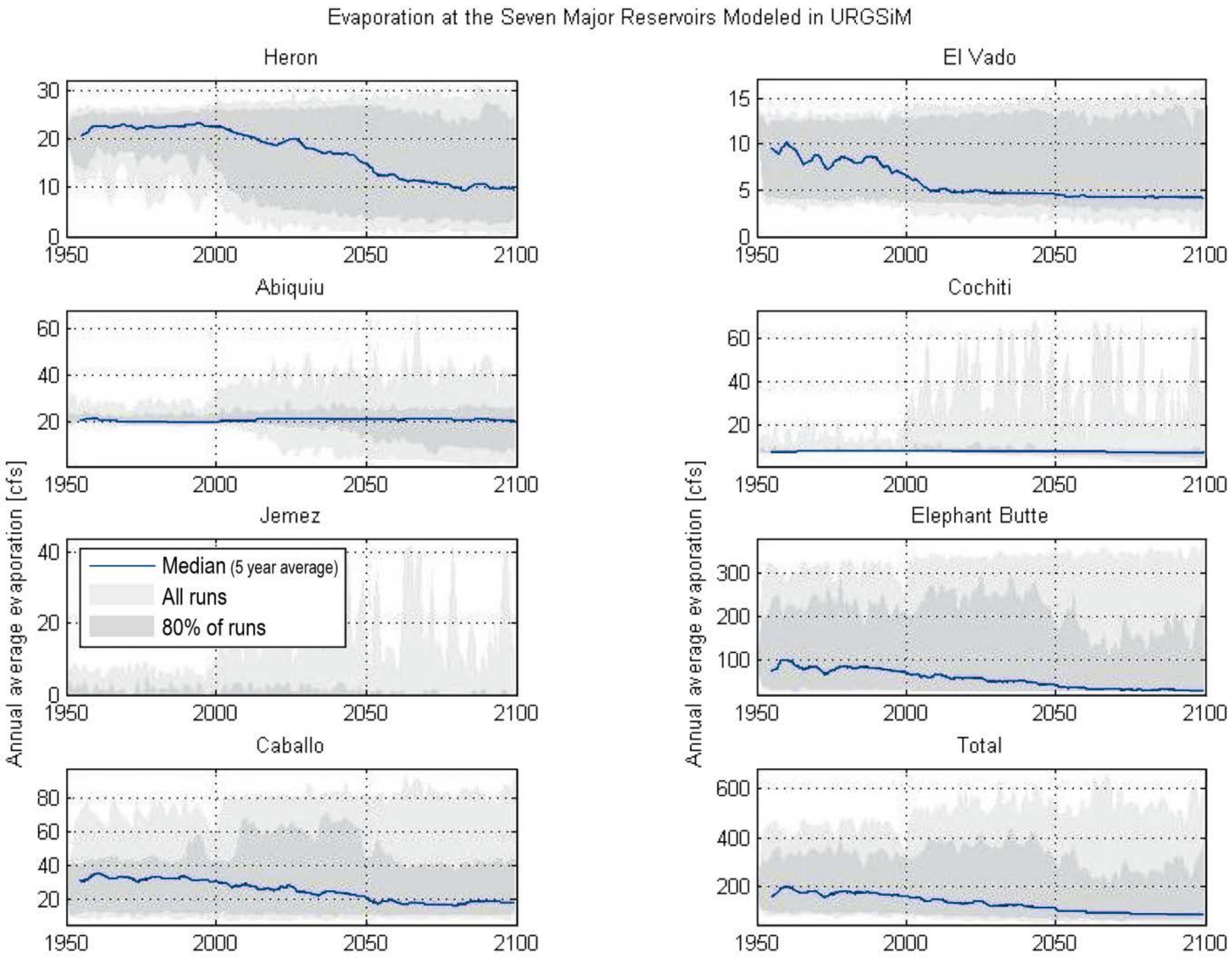

Figure 49.—Projected reservoir storage at the seven major reservoirs in the Upper Rio Grande system.

5.1.2 Hydropower Generation

The Upper Rio Grande system has three hydropower plants:

- **El Vado Dam and Powerplant.** Reclamation operates El Vado Dam under agreement with the Middle Rio Grande Conservancy District (MRGCD). The capacity is 8 megawatts.
- **Abiquiu Dam.** Built and operated by the USACE, the powerstation at the dam base is operated by Los Alamos County Department of Public Utilities. The total maximum storage of El Vado Reservoir is about 180,000 acre-feet. The capacity is about 16.5 megawatts.
- **Elephant Butte Dam and Powerplant.** A Reclamation facility, Elephant Butte Dam can store about 2 million acre-feet of water to provide irrigation and year-round power generation. A court order has restricted power generation during non-irrigation months. The installed capacity is about 28 megawatts.

In these hydropower-generation systems, lower flows and lower reservoir levels associated with climate change are projected to lead to less hydropower generation. Figure 50 provides the analysis results for the ensemble of simulations for hydropower generation. Figure 50 shows that the projected decrease is substantial, from an initial generation of about 15 megawatts, the rate drops almost 50 percent to about 8 megawatts by the end of the century, with most of the decrease coming during the months of May through September. El Vado Dam sees the smallest average decline in hydropower output, while Elephant Butte Dam sees the largest.

Under the Compact Compliance Scenario (which assumes that New Mexico takes management actions to assure compact delivery) decreases to Elephant Butte Dam hydropower—and thus to overall hydropower—are slightly less than under the Base Case Scenario. Figure 51, shows the difference between the Base Case Scenario and the Compact Compliance Scenario. As seen in Figure 51, the difference is small, although the difference becomes more apparent in the last several decades of the simulations.

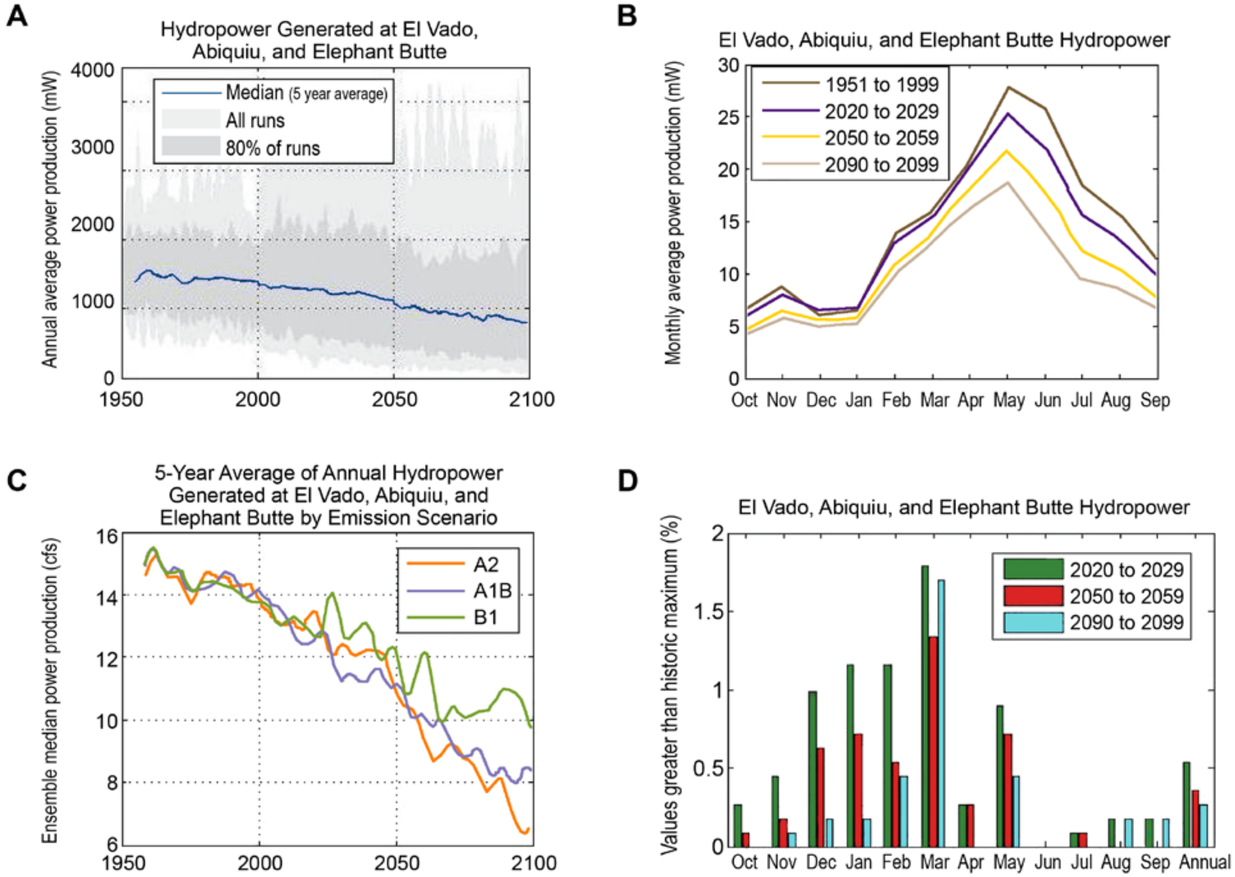

Figure 50.—Projected combined hydropower generation from Abiquiu, El Vado, and Elephant Butte Reservoirs under the Base Case Scenario.

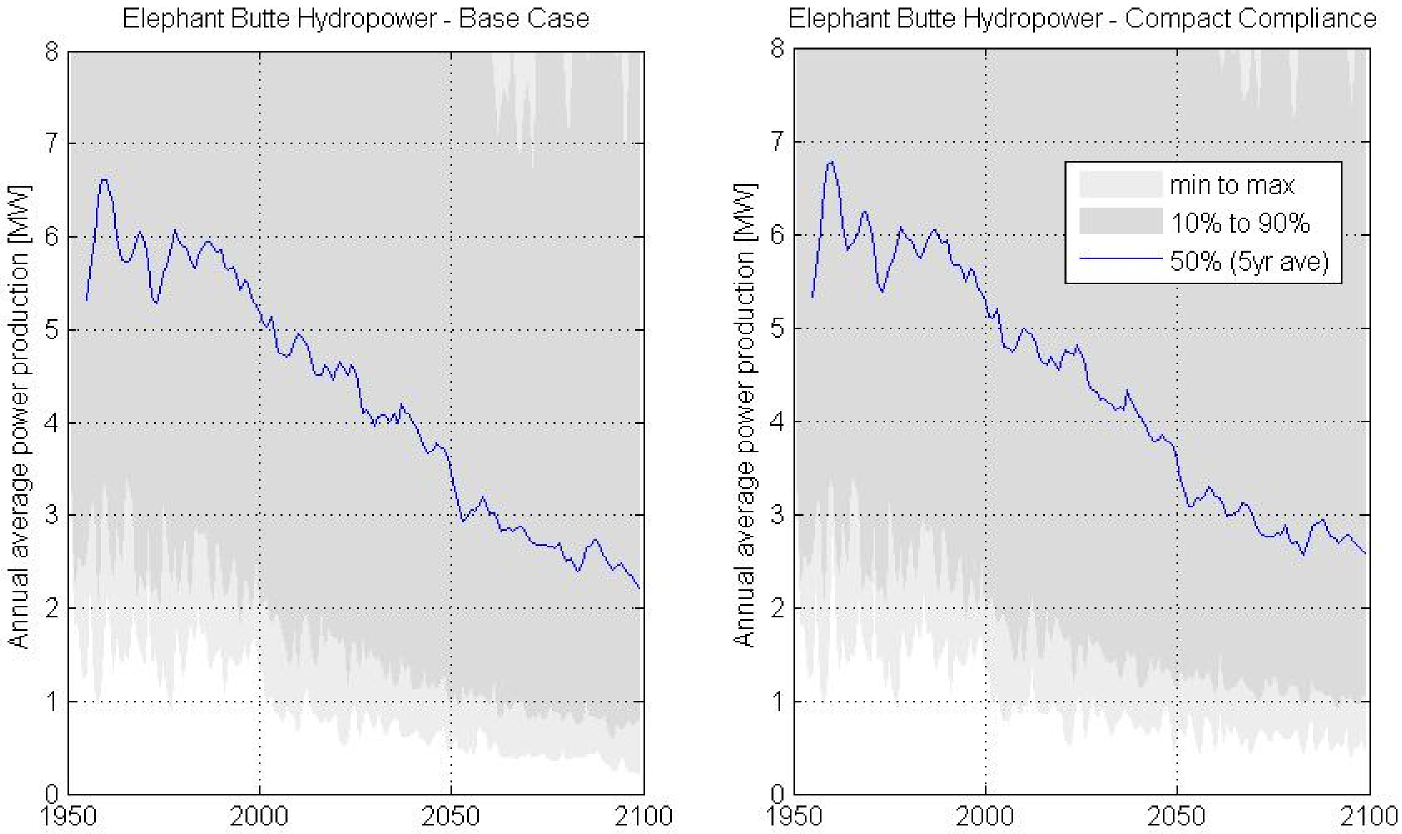

Figure 51.—Simulated hydropower generation from Elephant Butte Dam for the Base Case (left) and the Compact Compliance Scenarios (right).

5.2 Flood Control Operations

The operations model used for this study, URGSiM, is a monthly time step model, and so the model is not inherently suited to detailed evaluations of flood control capacity. However, despite this weakness, some initial general observations are still valuable. The inflow predictions increase in variability as the simulations progress, with annual and monthly flows occurring from 2000 through 2099 period that exceed historic observations from 1950 through 1999 for all supply inputs.

Our analyses project that streamflows would get more and more variable as time progresses. Abiquiu, Cochiti, and Jemez reservoirs are the main flood control reservoirs on the system as these reservoirs reserve storage capacity for flood control. The storage projections for these reservoirs (Figure 49) offer visual evidence that flood control operations would become more frequent in the system, even as average supplies decrease. The extreme flows are projected to become more extreme with climate change, and thus flood control operations would occur more often in the future. Elephant Butte and Caballo reservoirs are not included in this analysis, since they are combined water storage and flood-control reservoirs.

To gain a quantitative estimate of the sufficiency of flood control storage at Abiquiu and Cochiti reservoirs, we can look at how often these primarily flood control reservoirs fill to within 99 percent of capacity. Results from such analyses are summarized in Table 3. Additional analysis with a finer time resolution and more in depth exploration of resulting downstream flows would be necessary to confirm and quantify the magnitude of this additional flood control risk.

Table 3.—Instances of insufficient flood control capacity in Abiquiu, Cochiti, and Jemez reservoirs by major period

Reservoir	Simulation period (years)	Months with insufficient flood control capacity	Years with insufficient flood control capacity
Abiquiu	1950 – 1999 (49)	0 (0%)	0 (0%)
Cochiti		0 (0%)	0 (0%)
Jemez		0 (0%)	0 (0%)
Abiquiu	2000 – 2049 (50)	4 (0.006%)	4 (0.07 %)
Cochiti		172 (0.3 %)	47 (0.8 %)
Jemez		6 (0.009%)	6 (0.009%)
Abiquiu	2050 – 2099 (50)	5 (0.007 %)	3 (0.05 %)
Cochiti		110 (0.2 %)	26 (0.5 %)
Jemez		4 (0.006%)	4 (0.07 %)

5.3 Water Quality

Although assessing the potential impacts of climate change on water quality was beyond the scope of the URGIA, a recent Environmental Protection Agency (EPA) study considered climate change impacts to water quality in the Rio Grande Basin above the confluence with the Rio Puerco (Hydrologic Unit Codes [HUC] 1301 and 1302) (EPA 2013). In the EPA analyses, absolute reductions in total nitrogen, phosphorous, and suspended solids loads reflect reductions in total flow volumes. However, projected reductions do not reflect how the concentration of these pollutants may change under future climate scenarios. Concentrations of these and other pollutants, and of salt, may increase in the future under projected warming scenarios in response to increased evaporation rates for surface water and increased precipitation intensity that could wash a greater volume of pollutants from the land surface into the river.

Although urban areas constitute a negligible share of the total Rio Grande watershed above the Rio Puerco confluence, continued development in the Albuquerque Metropolitan Area is likely to make a greater quantity of pollutants available over time to reaches of the Rio Grande downstream of this urban area, even as flow volumes decline.

5.4 Fish and Wildlife Habitat, Including Species Listed under the Endangered Species Act

5.4.1 Environmental Flow Targets

The operational modeling performed for this study included a simplified representation of river flow targets to support the needs of endangered species on the Rio Grande in New Mexico, as laid out in a 2003 Biological Opinion for water and flood control operations on the Middle Rio Grande (U.S. Fish and Wildlife Service [FWS] 2003). These flow targets are specified for at Central Avenue Bridge in Albuquerque, below the Isleta Diversion Dam (approximately 15 miles downstream of Central Avenue), and above the San Acacia Diversion Dam (approximately 67 miles downstream of Central Avenue). Although new management strategies and a new Biological Opinion are under development, these flow targets serve as a reasonable example of the requirements for fish and wildlife, including ESA-listed species.

Figure 52 provides the analysis results for the ensemble of simulations for the flow deficits occurring at Central Avenue and below Isleta Diversion. The two locations are combined because only one of the two is ever in effect in a given year. Compact Articles VI and VII, and thus the Central Avenue targets, are in effect during the majority of simulation years.

These deficits rise with time and are most significant in September, when there is an 8 cfs average deficit in the 2090s, compared to a less than 1 cfs deficit from 1950 through 1999. In the exceedance probability graph (Figure 52, Panel C) the projections show a deficit in June through September by the 2090s, almost 30 percent of the time, and that 10 percent of the time in the 2090s, this deficit exceeds 30 cfs averaged over the 4-month summer period. Figure 52 provides the analysis results for the ensemble of simulations for the target flow deficits above the San Acacia Diversion Dam. Like the deficits at Central Avenue and below Isleta Diversion, the San Acacia deficits increase in both likelihood and magnitude over the next century.

However, the nature of these targets makes them most difficult to meet in June early in the simulations, and both May and June by the 2090s, when the average monthly target flow deficit is almost 40 cfs in both months as compared to less than 5 cfs from 1950 through 1999. The exceedance probability graph (lower left graph of Figure 47) shows that by the 2090s, there is some target deficit above the San Acacia Diversion in more than 40 percent of simulated years, and that that target deficit is greater than 80 cfs averaged from April through July in 20 percent of years from 2000 through 2099.

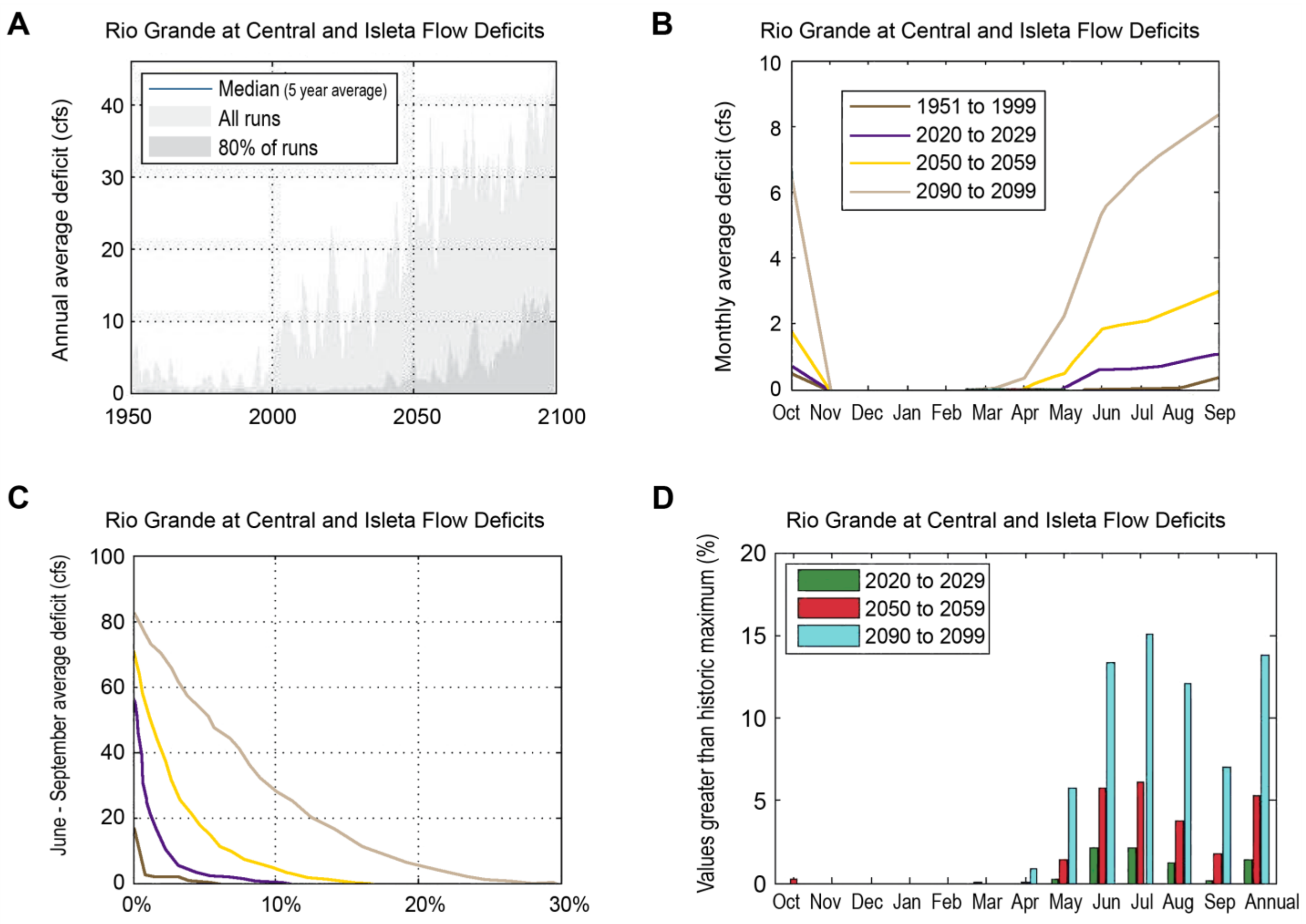

Figure 52.—Projected deficits relative to current (2003) environmental flow targets on the Rio Grande at Central and the Rio Grande at Isleta (only one of which can occur at a time).

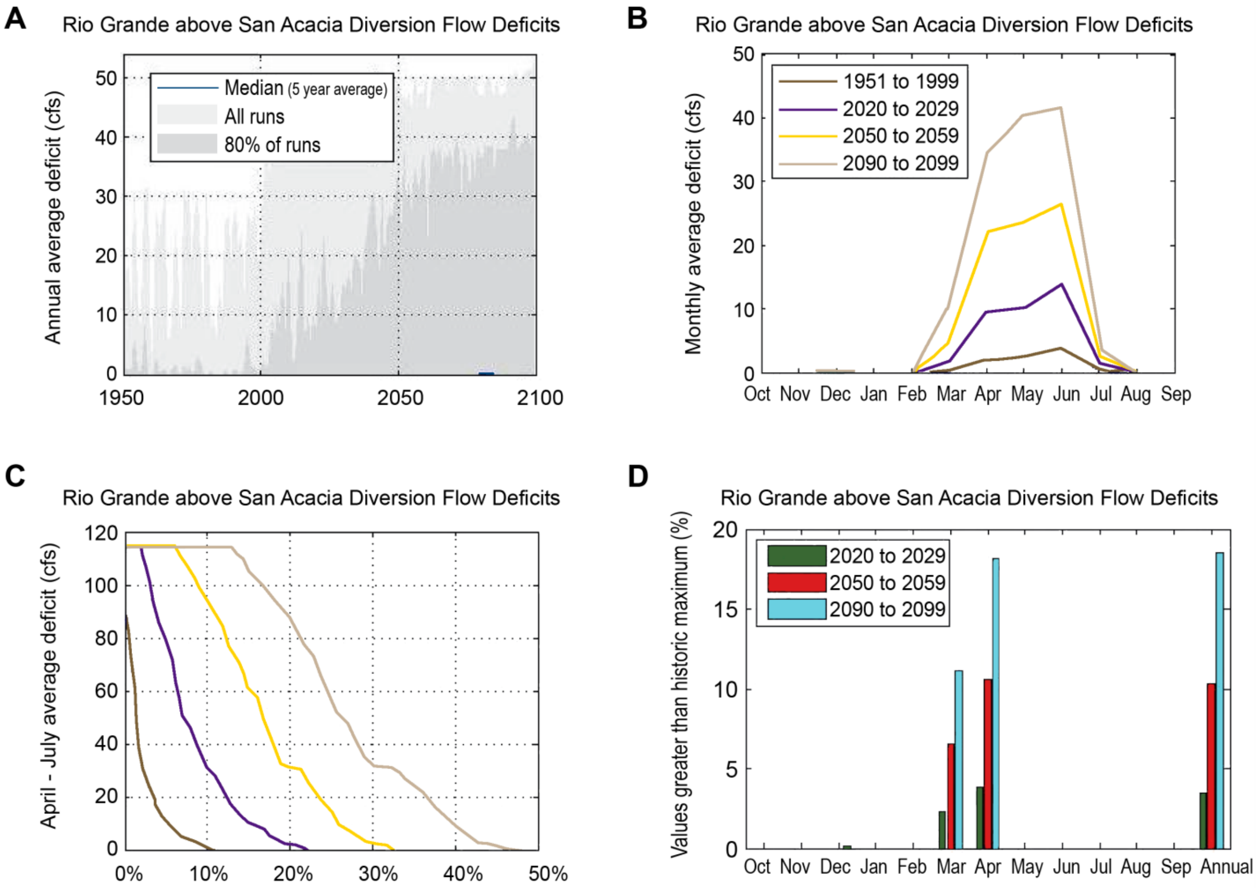

Figure 53.—Projected deficits relative to current (2003) environmental flow targets on the Rio Grande above the San Acacia Diversion Dam. There are no targets and thus no deficits from August through October.

5.4.2 Bosque Water Stress

The model used for this study, URGSiM, does not expand or contract riparian vegetative area in response to water availability. For the Base Case Scenario, which constrains the analysis to examine climate change impacts only, the riparian area remains the same throughout time for all simulations. However, the health of the riparian corridor (termed “the Bosque” when referring to the riparian vegetation along the Rio Grande between Cochiti and Elephant Butte reservoirs, including the Jemez River) may vary through time depending on water availability. We use the difference between the potential and actual ET in the Bosque as an indication of water stress, which would be expected to be inversely related to the health of the ecosystem, and thus perhaps an indirect indicator of wildlife habitat quality in the riparian corridor.

Figure 54 provides the analysis results for the ensemble of simulations for the simulated Bosque water stress, measured as the difference between potential and actual water consumption, between Cochiti and Elephant Butte reservoirs, including the Jemez River. The projections show Bosque water stress rising by almost 40 percent over the course of the next century, from around 90 cfs from 1950 through 1999 (approximately 30 percent of potential) to around 130 cfs by 2090s (approximately 40 percent of potential). In other words, the Bosque goes from getting about 70 percent of what it could use under ideal circumstances during the historic period, to getting about 60 percent of what it could use under ideal circumstances by the 2090s. This decrease in water use as a function of potential is driven by increasing potential demand and dropping shallow ground water levels, and would be expected to have negative impacts on the health of the vegetation in the riparian corridor. This is a result of drops in average shallow groundwater levels as shown in Figure 54.

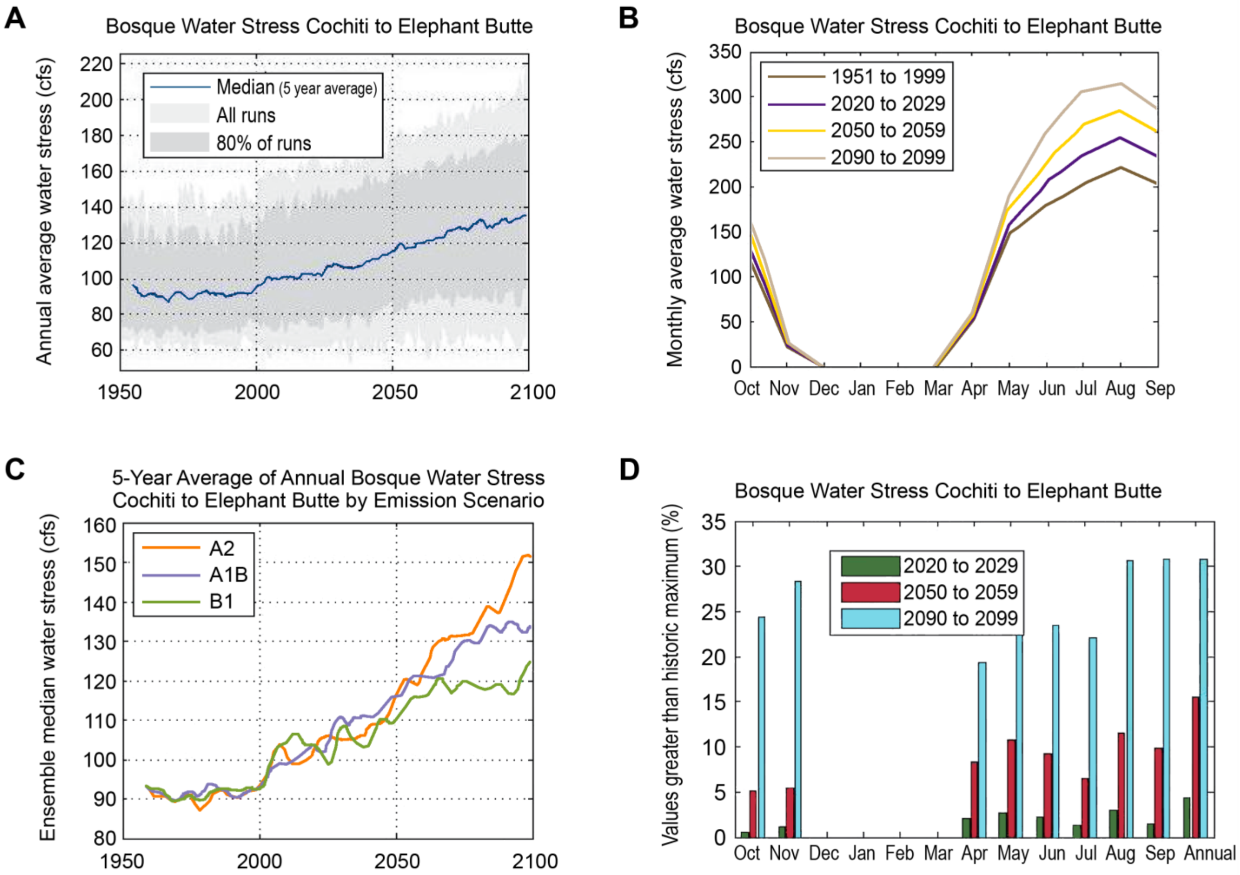

Figure 54.—Projected water stress in the Bosque in the reach between Cochiti and Elephant Butte Reservoirs, including the Jemez River.

5.4.3 Fish and Wildlife Habitat

Climate change results in a reduction of water in the Upper Rio Grande system resulting from decreased supplies coupled with increased demands. This reduction in water is expected to make environmental flows in the river more difficult to maintain, and reduce the shallow groundwater available to riparian vegetation. Both of these impacts have implications on the habitat of fish and wildlife in the Upper Rio Grande riparian system.

While the inability to meet flow targets is an indirect method to estimate the impact of climate change on riverine habitat, the results of these indicators are not ambiguous: there would be less water in the river, and low flow-related biological requirements would be more difficult to meet. It is possible that the extreme high flow events which grow in frequency through the runs would create positive benefit to biological habitat; however that analysis is beyond the ability of the monthly timestep model used for this study.

In August 2013, the U. S. Forest Service released an assessment of the potential effects of climate change on terrestrial species living along the Middle Rio Grande in New Mexico (Friggens et al. 2013). The study team evaluated 117 species of birds, reptiles, amphibians, and mammals and their vulnerability to such changes as altered timing of precipitation events and river flows, as well as reduced overall river flows and water availability. The study projected a decreasing availability of riparian habitat, and loss of mature trees due to fire and disease, which would directly and indirectly affect many species of birds and mammals. Most of the species evaluated were projected to experience negative effects from climate change. However, a few species, such as coyotes, jackrabbits, some lizards and road runners may benefit from conversion of the bosque to a more sparsely vegetated and drier habitat.

The interactions between climate and ecological systems are a two-way street. Climate plays a key role in determining the distribution and biophysical characteristics of habitats and ecosystems that provide the ecological resources needed for life. However, climate is not solely driven by atmospheric, oceanic, and terrestrial physical processes. Biological processes likewise affect climate, as do human responses to these biological processes. As future climate changes occur, these dynamic interactions would continue to affect ecological resources such as flow, water quality and many other ecosystem characteristics that impact endangered species and other fish and wildlife.

5.4.4 Listed Species

Species listed under the ESA that have habitat within the Upper Rio Grande include the:

- Rio Grande silvery minnow (Hybognathus amarus; silvery minnow)
- Southwestern willow flycatcher (Empidonax traillii extimus; flycatcher)
- Pecos sunflower (*Helianthus paradoxus*, sunflower)

The URGIA only addresses the federally-listed endangered species, but these species are also listed as endangered under the New Mexico Wildlife Conservation Act. The historic development of the Upper Rio Grande has had impacts on these listed species and their habitats, and climate change promises to exacerbate those impacts, primarily through decrease in streamflows and available water to support riparian habitat. Each of these species depends in some way on flood flows and floodplain interconnection. Overbank flow events are projected to become less common in future years, although an increase in extreme events is also forecast, which could increase floodplain connection but also have other consequences. Long periods of lower flows may also increase the process of channel narrowing, which is decreasing available riverine and riparian habitat.

5.5 Flow- and Water-Dependent Ecological Resilience

The responses of natural systems to progressive changes in climatic conditions are not linear. Instead, natural systems tend to be stable within a certain degree of change, as determined by the system’s resilience (or resiliency), and then rapidly change when the system’s degree of tolerance is exceeded. For this reason, ecological resilience is a useful concept for understanding the responses of ecological systems to climate change. The following definitions of ecological resiliency are generally representative of those in the literature:

- The capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks (Folke et al. 2004 and Walker and Meyers 2004).

- The capacity of an ecological system to absorb internal and/or external change while exhibiting a similar set of structures and processes (i.e., remaining within a regime). If an ecological system’s resilience is “eroded,” the system becomes vulnerable to regime shifts, which involves the system shifting from one regime to another regime characterized by a different set of structures and processes. Regime shifts are indicative of non-linear dynamics, and the weight of evidence suggests that ecological, and other complex systems exhibit multiple regimes (Benson and Garmestani 2011).

Ecological thresholds are transition points in which a small change in a physical or chemical parameter or a component of a system elicits a large, or non-linear, response of a natural or social-ecological system. A threshold represents the endpoint of ecological resilience—the point at which a system switches into a new paradigm. Avoiding these thresholds is often a key management goal in climate-change adaptation.

It should be noted that ecosystem resilience is not always desirable. Many Western ecosystems have been significantly altered and have crossed thresholds to the point that the current ecosystems may be dominated by non-native species and processes or may have low biodiversity. These ecosystems may not be healthy, or hospitable to native plants and animals, but may be highly stable, or resilient. In such cases, decreasing the ecological resiliency of the system may be one of the strategies identified to promote ecosystem health.

In the Upper Rio Grande Basin, the available water supply is low relative to the demand for water. Ecological and human systems within the basin already operate close to thresholds related to available water supply. In the future, if projected water supplies decrease and demands increase, water availability thresholds may be crossed, and key systems may undergo regime shifts. It has been suggested (Williams et al. 2010), that forests in some parts of New Mexico, such as the Jemez mountains, may have crossed a threshold. Moisture stress in the trees has led to bark beetle infestations and fire, and the forest may be undergoing a transition even now to a new ecosystem, with new structures, processes, and species.

Many parts of the Upper Rio Grande system are also near thresholds with respect to snowpack temperatures. In areas where the winter snowpack temperatures are already close to the freezing point, a small increase in temperature could lead quickly to a large decrease in the region's ability to store winter moisture in snow for use during the summer. To some degree, Reclamation's storage reservoirs mitigate for this vulnerability, in that they can store water from winter snows that melt and make that water available later in the season.

The large swaths of riparian tamarisk (salt cedar) that dominate the Rio Grande corridor just upstream of Elephant Butte Reservoir and the reservoir delta are examples of resilient systems that are not considered desirable. Although water managers may wish to switch this ecosystem into a new paradigm, the system's resilience, driven by the tamarisk's high degree of adaptation to current conditions, will make this difficult.

These are just a few examples of the resilience and vulnerabilities of water-dependent systems in the Upper Rio Grande. Evaluation of potential adaptation and mitigation strategies to respond to the hydrologic impacts of climate change in this basin, as will be done in future basin studies, will require a more detailed analysis of the key thresholds associated with social-ecological systems in the basin. It is likely that, in the Rio Grande system, adaptation will involve management of transitions into new State's for social-ecological systems, rather than simply building of resilience to the old states.

5.6 Recreation

The Upper Rio Grande Basin offers a number of water-dependent recreational activities, which are likely to be affected by climatic changes that affect the system hydrology. These activities include:

- Fishing along the Conejos River and Rio Grande in Colorado, along the Rio Grande between Taos Junction Bridge and Embudo in New Mexico, and in Heron, El Vado, Abiquiu, Elephant Butte, and Caballo reservoirs
- Camping along the Rio Grande in Colorado and New Mexico, including below Taos Junction Bridge, along the Rio Chama above Abiquiu Reservoir, and at Heron, El Vado, Abiquiu and Elephant Butte Reservoirs
- White-water boating along the Rio Grande above Embudo, and between El Vado and Abiquiu reservoirs on the Rio Chama
- Flat water boating in Heron, El Vado, Abiquiu, Cochiti, Elephant Butte and Caballo reservoirs

Increased summer and winter temperatures may increase the popularity of these water-based activities. Moreover, reduced supplies, altered timing of flows, and increased variability will change the availability and nature of these recreational opportunities.

5.6.1 Recreation at Reclamation and U.S. Army Corps of Engineers' Reservoirs

Water level fluctuations at reservoirs affect recreation use and economic value in a variety of ways through changes in water depth and surface acreage. (Platt, Bureau of Reclamation 2000) Extended periods of low reservoir levels at Heron, El Vado, Elephant Butte, and Caballo reservoirs may affect overall visitor numbers and the revenue stream to New Mexico State Parks, the managing entity for those reservoirs. Changes in usage during the most recent drought (2011 through 2013 thus far), may shed light on how the usage may changes under the projected conditions. Elephant Butte Reservoir, the largest park in the state park system and the most popular destination for boaters, experienced a decline of more than 100,000 visitors during the drought year 2012 compared to reported visitor numbers for 2009, 2010, and 2011. Reported visitation at the USACE's reservoirs, Abiquiu Lake and Cochiti Lake, also generally declined between the pre-drought year 2009 and the drought year 2012, with exceptions of an increase at Cochiti in 2010 and an increase at Abiquiu during 2011. Revenues at both reservoirs declined accordingly (USACE reservoir visitation and revenue records, May 2013).

Water-based recreation is also susceptible to impacts of cascading changes, such as from debris flows caused by rainstorms over fire scars. For example, Cochiti Lake experienced a drastic decline in visitation during 2011 due to an extended closure, which resulted from large debris flows and the threat of flooding in the aftermath of the Las Conchas Wildfire in the Jemez Mountains. Such impacts may become more common as the climate changes to a hotter and drier one.

5.6.2 Whitewater Rafting and Fishing

New Mexico has two very attractive recreational tourism assets in its National Wild and Scenic Rivers, the Rio Grande and Rio Chama. Figure 55 provides the analysis results for the ensemble of simulations for projected river flow for two prime locations for whitewater rafting and kayaking within these reaches, the Rio Grande near Embudo (the downstream end of the Rio Grande Gorge and Rio Grande del Norte National Monument) and the Rio Chama below El Vado (the Wild and Scenic reach of the Rio Chama). River flows in these reaches are projected to decline overall, but those low flows are punctuated by more frequent extreme flow events. Thus, the quality of white-water boating opportunities over the next century on these two rivers would decrease, punctuated by occasional flows which may appeal to highly skilled boaters.

The impact of low streamflows is highly influential in net business performance for the state’s whitewater boating industry (Harris, Personal Communication, 2013), with an obvious correlation between low flows and reduced revenues. The industry’s overall revenue pattern during the current drought has been steadily downward. While no business failures have occurred yet, several companies are concerned about their increasing levels of debt and decreasing ability to retain employees.

The following are desired flow levels for whitewater rafting in popular runs on the Upper Rio Grande (Harris, Personal Communication, 2013):

- Above 600 cfs for the most desirable trip, the Class 4 Taos Box, (this reach is unnavigable below 600 cfs)
- Above 200 cfs for the half-day Pilar Racecourse

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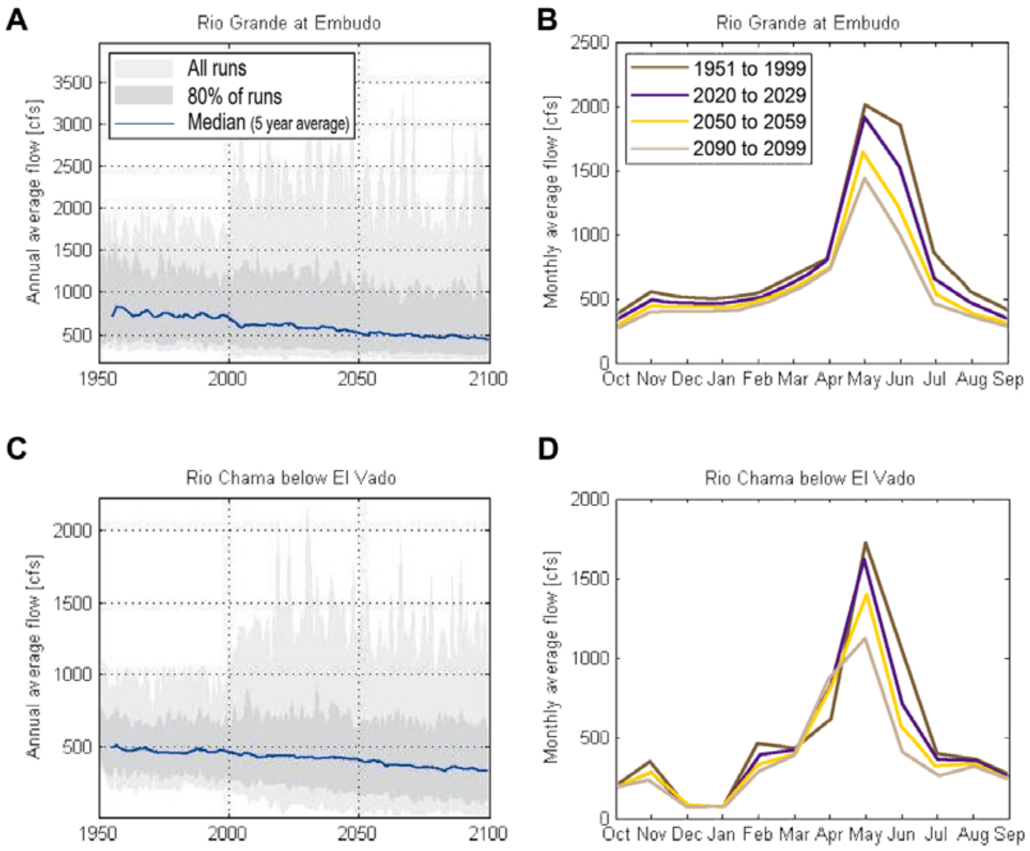

Figure 55.—Projected annual flows for all model runs and projected monthly average flows by period for the Rio Grande at Embudo, and the Rio Chama below El Vado.

- Above 300 cfs for the multi-day wilderness trip on the Rio
- Above 400 cfs for the one-day Lower Rio Chama trip (the "Monestary Run")

In 2013, outfitters holding permits for both the Rio Grande and Chama were able to shunt business from the very low Rio Grande to the regulated, thus higher flow, Rio Chama. Outfitters who did not have Chama permits and thus no convenient fall-back offering reported 50 percent reduction in revenues compared with 2012 (Harris, Personal Communication, 2013).

Fishing outfitters and guides report a steadier business performance than boating operators, but most cite long-term concern with flow related population trends that could affect their target species, thus their business.

6. Summary and Next Steps

6.1 Summary of Findings

Reclamation developed hydrologic projections for the Upper Rio Grande Basin over the next century, based on the modeled climate projections described in Chapter 3. The water operations modeling for the Upper Rio Grande Basin using these hydrologic projections as input (presented in Chapter 4) paints a picture of a changing hydrology for the Upper Rio Grande Basin.

The analysis presented in this report attempts to project the impacts of climate change alone on the water supply and demand within the Upper Rio Grande Basin, rather than predict what the future would look like in this basin. The future will depend on numerous societal choices. The hydrologic changes that are projected to result from climate change in the Upper Rio Grande Basin would be compounded by the numerous other changes we will make to our landscape and our water supply and distribution.

6.1.1 Impact Assessment: Climate and Basin Hydrology

An analysis of gage records showed a warming trend in the Upper Rio Grande Basin over the past four decades. Average temperatures increased by almost 0.7°F per decade, resulting in a total average warming since 1971 of over 2.5°F. Based on modeled climate-change projections for temperatures in the Upper Rio Grande Basin will rise an additional four to six °F by the end of the 21st century. Model simulations did not, however, consistently project changes in annual average precipitation, although they did project changes to the timing, form (i.e., rain or snow), and spatial distribution of that precipitation. Also, increases in temperature alone could significantly decrease the available water in the basin, due to increases in evaporation and water use by plants (i.e., evapotranspiration).

The projections presented in the Upper Rio Grande Impact Assessment present a picture of changing hydrology for the Upper Rio Grande, with implications for water management, human infrastructure, and ecosystems. Although there are uncertainties in the details, some general patterns are clear. This section presents a discussion of possible implications of those general patterns.

Decreases in water availability.

- Our usable, manageable water supply is projected to decline. The URGIA models along with projections from previous studies indicate a loss of winter snowpack and an increase in evaporation and water use by plants, which would result in a decrease in available water supply. Simulated average supplies of all native sources to the Upper Rio Grande Basin would decrease on average by about one third, while flows in the tributaries which supply the imported water of the San Juan-Chama Project would decrease by about one quarter.

  A decrease in the storage of water supply as snow decreases the amounts available for use during the irrigation season/summertime. There would also be an increase in all outside demands (including agricultural, riparian, and urban landscaping) due solely to the projected increases in temperature. The decrease in water supply would be exacerbated by the increase in demand; the gap between supply and demand will grow even if there are no decreases in precipitation.

  The growing imbalance between supply and demand would likely lead to a greater reliance on non-renewable groundwater resources. Increased reliance on groundwater resources will lead to greater losses from the river into the groundwater system.

- **Changes in the timing and spatial distribution of flows.** The seasonality of flows changes dramatically for the Colorado headwater flows, the Chama and Jemez flows, and the San Juan-Chama Project tributary flows. There would also be changes in the geographic distribution and timing of runoff. Although the projections here do not portray it, other studies (for example Asmerom et al. 2013) have indicated some potential for strengthening of the summer monsoon, and therefore for an increase in the portion of the basin's precipitation that falls in the summertime. These flows are downstream of our current ability to store that water. The projections suggest a somewhat more reliable supply from the San Juan-Chama Project (as long as there is no across-the-board decrease in available supply in the Upper Colorado River system) than for the native Rio Grande supply.

- **Increases in the variability of flow.** In all cases the projections show an increase in variability in meteorological conditions (temperature and precipitation) and in runoff volume from month to month and year to year as the simulations progress.

Water operations modeling for the Upper Rio Grande Basin using these hydrologic projections as input suggests that increasing water demands within the basin will exacerbate the gap between supply and demand. Such changes would lead to water management challenges for Reclamation and other water managers within the Upper Rio Grande Basin.

Feedbacks can lead to cascading impacts. For example, more intense droughts and higher temperatures recently led to a greater moisture deficit in the region’s forests in New Mexico. Trees that aren’t getting enough water are more susceptible to beetle infestations, and infected weakened and dead trees are more susceptible to catastrophic wildfires. Thunderstorms tend to build over fire scars because heat builds up over the blackened ground, and intense thunderstorms on the fires scars lead to the washing of ash into rivers, and to debris flows. Ash in the rivers can lead to decreased oxygen in the water and cause fish kills. Debris flows can lead to sediment accumulation in our reservoirs, and sediment accumulation in our reservoirs can lead to less flood protection for downstream human infrastructure, and so on.

6.1.2 Water Management Implications

This URGIA analysis presents projected impacts to Upper Rio Grande Basin in terms of the parameters defined in the SWA as discussed in Chapter 5. The URGIA analysis showed the following results:

- **Water Infrastructure and Operations, and Water Delivery.** The reduced surface-water inflows to the Upper Rio Grande Basin, coupled with increased irrigated agricultural and riparian vegetation demands, would result in decreased reservoir storage throughout the system, with commensurate decreases to water delivery.

- **Hydropower Generation.** Lower flows and lower reservoir levels associated with climate change are projected to lead to less hydropower generation. The projected decrease is substantial. From an initial generation within the Upper Rio Grande system of around 15 megawatts, the rate would drop to almost 50 percent to around 8 megawatts by the end of the century, with most of the decrease occurring from May through September.

- **Flood Control Operations.** Extreme flows are projected to become even more extreme and more frequent with climate change, and thus flood control operations would be needed more often in the future, and would need to mitigate for even larger floods.

- **Water Quality.** Concentrations of nitrogen, phosphorus, suspended solids, and salt in surface waters throughout the system are projected to increase in the future due to higher evaporation rates for surface water. In addition, runoff from the projected higher intensity precipitation may wash a greater volume of pollutants into the river, despite a decreased overall flow volume.

- **Fish and Wildlife Habitat, Including Endangered Species Act (ESA) Listed Species and Critical Habitat.** Climate change is projected to reduce available water in the Upper Rio Grande Basin. This reduction in water is expected to make environmental flows in the river more difficult to maintain, and reduce the shallow groundwater available to riparian vegetation. Both of these impacts could alter habitat conditions for fish and wildlife in the Upper Rio Grande Basin riverine and riparian ecosystems.

- **Flow and Water-Dependent Ecological Resiliency.** Ecological and human systems within the basin already operate close to thresholds (i.e., points at which small changes could have larger-scale repercussions) related to available water supply. It is possible that some systems in the basin have already undergone regime shifts. In the future, as projected water supplies decrease and demands increase, water-availability thresholds may be crossed, and key systems may change their basic structure and function.

- **Recreation.** Water-based recreation at Reclamation and USACE reservoirs, and river-based recreation, including whitewater rafting and fishing, may be negatively impacted by the projected decreases in flows.

- **The Rio Grande Compact.** Analyses presented in this report assume that Colorado would use its ability for priority administration to assure its obligations are met under the Rio Grande Compact. However, the irrigation system would be significantly impacted. It is assumed that New Mexico would take additional management actions to meet its obligations; therefore, under the Compact Compliance Scenario, water availability to the Rio Grande Project would not be affected by delivery shortages.

6.2 Next Steps

6.2.1 Operational Modeling

Methods and tools for projecting the impacts of climate change are constantly being developed and refined. The projections and analysis presented in this report represents a solid first step in the assessment of potential impacts in the Upper Rio Grande Basin, based on the best science and tools available at the time of initiation of the study. However, as our understanding is improved of the way atmospheric, oceanic, and ecological processes are changing, and how feedbacks either mitigate or exacerbate these changes, our models will be refined, and our ability to project changes will be improved. It is therefore hoped that this study represents the first of a number of steps that Reclamation takes, in cooperation with its local partners, to project the water management challenges of our future.

Efforts are currently underway to perform operational modeling of climate projections for the Upper Rio Grande on a daily timestep, using the Upper Rio Grande Water Operations Model (URGWOM). Such daily-timestep projections can provide information on the ways that the projected impacts would be experienced by humans, fish, and wildlife on the timescale at which we all experience our river system, on a daily basis.

In addition, it is hoped that future analyses can be performed using the CMIP5 suite of GCM simulations that is associated with the most recent efforts of the IPCC.

6.2.2 WaterSMART Basin Study Program Activities

As mentioned in section 1.4, this WaterSMART West-Wide Climate Risk Assessment (WWCRA) Impact Assessment establishes a baseline characterization of how climate change may impact water supply, demand and key water-management activities, as called for in the SWA. This Impact Assessment allows Reclamation to fulfill requirements under the SWA to better understand how its facilities, operations and water delivery commitments to its customers may be affected by climate change. To accomplish these objectives, Reclamation has assessed the potential impacts of climate change alone, without attempting to project what future development or management actions may be, including how population may change, how power generation may evolve, or how land use, including the amount and type of irrigated agriculture, may change. While factors such as these would undoubtedly be affected by climate change, these factors are also changing due to societal and economic pressures that are independent of climate change.

Some WaterSMART Basin Study Program activities are available for stakeholders to pursue next steps:

- **Basin Studies.** Fully understanding risks and impacts of climate change will require a study team to evaluate not just the direct impacts of climate change, as projected in this study, but the secondary impacts that result from human responses to these changes, and the other developments that will go on with or without climate change. These other changes will need to be evaluated through a collaborative process that includes all of the necessary stakeholders in a basin. Reclamation's Basin Study Program has been developed to provide a framework for this collaborative process, and includes various options for stakeholders to build upon the results from a WWCRA Impact Assessment.

The Basin Studies are in-depth, water supply, demand and operations analyses that are cost-shared with stakeholders and selected through a competitive process. Through the Basin Studies, Reclamation works collaboratively with stakeholders to evaluate the ability to meet future water demands in a particular basin and to identify mitigation and adaptation strategies to address potential climate change impacts. More information about Basin Studies is available at <http://www.usbr.gov/WaterSMART/bsp/>.

- **Landscape Conservation Cooperatives.** In addition to the WWCRA Impact Assessments and the Basin Studies, the Basin Studies Program includes Landscape Conservation Cooperatives (LCCs). The LCCs are partnerships of governmental (Federal, State, Tribal and local) and non-governmental entities, and are an important part of the Department of the Interior's efforts to coordinate climate-change science activities and resource management strategies. The Desert and Southern Rockies LCCs span the upper and lower Colorado River Basin and, together, include portions of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Texas. Reclamation participates in LCCs encompassing the 17 Western states and is co-leading the Desert and Southern Rockies LCCs with the FWS to identify, build capacity for, and implement shared applied science activities to support resource management at the landscape scale. See <http://www.usbr.gov/WaterSMART/lcc/> for more information.

Reclamation is adding new activities to the Basin Studies Program that will provide stakeholders more opportunities to further refine adaptation strategies developed in Basin Studies. All of the existing and proposed activities within the Basin Study Program are complementary and represent a multi-faceted approach to the assessment of climate change risks to water supplies and impacts to activities in Reclamation's mission, as well as the identification of adaptation strategies to meet future water demands.

Currently, Reclamation is working on Basin Studies with the city and county of Santa Fe on the Rio Grande headwaters, the Santa Fe Watershed, and the San Juan-Chama Project and with the New Mexico Interstate Stream Commission on the Pecos River Basin. Reclamation is very much interested in partnering with other entities in the Upper Rio Grande. Please contact Reclamation's Albuquerque Area Office if you are interested in partnering with Reclamation on a Basin Study within the Upper Rio Grande Basin.

7. References Cited and Consulted

Allen, R. J., S. C. Sherwood, J. R. Norris, and C. S. Zender. 2012. Recent Northern Hemisphere Tropical Expansion Primarily Driven by Black Carbon and Tropospheric Ozone. Nature 485:350-354.

Anderies, J. M., M. A. Janssen, and E. Ostrom. 2004. A Framework to Analyze the Robustness of Social-Ecological Systems from an Institutional Perspective Ecology and Society **9**:18. Online: http://www.ecologyandsociety.org/vol19/iss11/art18/.

Andreadis, K. M. and D. P. Lettenmaier. 2006. Trends in 20th Century Drought over the Continental United States. Geophys. Res. Lett. **33**:L10403.

Andreadis K. M., P. Storck, and D. P. Lettenmaier. 2009. Modeling Snow Accumulation and Ablation Processes in Forested Environments. Water Resources Research **45**: W05429, doi:10.1029/2008WR007042.

Army Corps of Engineers. See U.S. Army Corps of Engineers.

Asmerom, Y., V. J. Polyak, J. B. T. Rasmussen, S. J. Burns and M. Lachniet. 2013. Multidecadal to Multicentury Scale Collapses of Northern Hemisphere Monsoons over the Past Millennium. Proceedings of the National Academy of Sciences, May 28, 2013. Online: http://www.pnas.org/cgi.doi/10.1073/pnas.1214870110.

Balling, R. C. and G. B. Goodrich. 2010. Increasing Drought in the American Southwest? A Continental Perspective using a Spatial Analytical Evaluation of Recent Trends. Physical Geography **31**:293-306.

Barnett, T. P. and D. W. Pierce. 2009. Sustainable Water Deliveries from the Colorado River in a Changing Climate. Proceedings of the National Academy of Sciences of the United States of America **106**:7334-7338.

Barry, R. G. 2008. Mountain Weather and Climate. Cambridge University Press, Cambridge, United Kingdom.

Beniston, M. 2006. Mountain Weather and Climate: A General Overview and a Focus on Climatic Change in the Alps. Hydrobiologia **562**:3-16.

Benson, M. and A. Garmestani. 2011. Can We Manage for Resilience? The Integration of Resilience Thinking into Natural Resource Management in the United States. Environmental Management **48**:392-399.

Bonfils, C., B. D. Santer, D. W. Pierce, H. G. Hidalgo, G. Bala, T. Das, T. P. Barnett, D. R. Cayan, C. Doutriaux, A. W. Wood, A. Mirin, and T. Nozawa. 2008. Detection and Attribution of Temperature Changes in the Mountainous Western United States. Journal of Climate **21**:6404-6424.

Brekke, L. D., J. E. Kiang, J. R. Olsen, R. S. Pulwarty, D. A. Raff, D. P. Turnipseed, R. S. Webb, and K. D. White. 2009. Climate Change and Water Resources Management—A Federal Perspective. U.S. Geological Survey Circular 1331.

Brekke, L., T. Pruitt, and D. Smith. 2010. Climate Change and Hydrology Scenarios for Oklahoma Yield Studies. U.S. Department of the Interior, Bureau of Reclamation, Technical Memorandum 86-68210-2010-01.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional Vegetation Die-Off in Response to Global-Change-Type Drought. Proceedings of the National Academy of Sciences of the United States of America **102**:15144-15148.

Brower, A. 2008. ET Toolbox: Evapotranspiration Toolbox for the Middle Rio Grande, a Water Resources Decision Support Tool. Water and Environmental Resources Division, Technical Service Center, Bureau of Reclamation, Denver.

Carnell, R. E. and C. A. Senior. 1998. Changes in Mid Latitude Variability Due to Increasing Greenhouse Gases and Sulphate Aerosols. Climate Dynamics **14**:369-383.

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov. 2010. Future Dryness in the Southwest US and the Hydrology of the Early 21st Century Drought. Proceedings of the National Academy of Sciences of the United States of America **107**:21271-21276.

Cayan, D. R., M. Tyree, K. E. Kunkel, C. Castro, A. Gershunov, J. Barsugli, A. J. Ray, J. T. Overpeck, M. Anderson, J. Russell, B. Rajagopalan, I. Rangwala, and P. Duffy. 2013. The Southwest Climate of the Future - Projections of Mean Climate. Page 509 *in* G. Garfin, editor. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. NCA Regional Input Reports. Island Press, Washington, D. C.

Cherkauer, K. A., and D. P. Lettenmaier. 2003. Simulation of Spatial Variability in Snow and Frozen Soil Field. Journal of Geophysical Research **108** (D22): doi:10.1029/2003JD003575.

Christensen, N. S. and D. P. Lettenmaier. 2007. A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin. Hydrology and Earth System Sciences **11**:1417-1434.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer. 2004. The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change **62**:337-363.

Colorado Office of the State Engineer. (nd). Colorado's Decision Support Systems: Water Rights Online: http://cdss.state.co.us/onlineTools/Pages/WaterRights.aspx. Retrieved 5/6/2013.

Colorado, New Mexico, and Texas, the States of, 1938. Rio Grande Compact. Public Act No. 96, 76th Congress. Approved by the President May 31, 1939.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle. 2004. Long-Term Aridity Changes in the Western United States. Science **306**:1015-1018.

Cozzetto, K., I. Rangwala, and J. Neff. 2011. Downscaled Air Temperature and Precipitation Projections for the San Juan Mountain Region. Narrative on Regional Climate Model Projections Submitted to the San Juan Public Land Center, Durango, Colorado.

Crawford, C. S., A. C. Cully, R. Leutheuser, M. S. Sifuentes, L. H. White, and J. P. Wilber. 1993. Middle Rio Grande Ecosystem: Bosque Biological Management Plan. Rio Grande Biological Interagency Team, U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

Dai, A. 2011. Drought Under Global Warming: A Review. Wiley Interdisciplinary Reviews: Climate Change **2**:45-65.

Daly, C., D. R. Conklin, and M. H. Unsworth. 2010. Local Atmospheric Decoupling in Complex Topography Alters Climate Change Impacts. International Journal of Climatology **30**:1857-1864.

Darcy, J. E. 2010. Society Benefits from Adaptation to Water-Related Risks Posed by Climate Change. U. S. Army Corps of Engineers, Office of the Assistant Secretary of the Army (Civil Works).

Diffenbaugh, N. S., J. S. Pal, R. J. Trapp, and F. Giorgi. 2005. Fine-Scale Processes Regulate the Response of Extreme Events to Global Climate Change. Proceedings of the National Academy of Sciences of the United States of America **102**:15774-15778.

Dominguez, F., J. Canon, and J. Valdes. 2010. IPCC-AR4 Climate Simulations for the Southwestern US: the Importance of Future ENSO Projections. Climatic Change **99**:499-514.

Enquist, C. A. F. and D. F. Gori. 2008. Implications of Recent Climate Change on Conservation Priorities in New Mexico. The Nature Conservancy, New Mexico.

Environmental Protection Agency. See U.S. Environmental Protection Agency.

Fish and Wildlife Service. See U.S. Fish and Wildlife Service.

Foden, W., G. Mace, J.-C. Vie, A. Angulo, S. Butchart, L. DeVantier, H. Dublin, A. Gutsche, S. Stuart, and E. Turak. 2008. Species Susceptibility to Climate Change Impacts. Pages 77-87 *in* J.-C. V. Vie, C. Hilton-Taylor, and S. N. Stuart, editors. Wildlife in a Changing World: An Analysis of the 2008 IUCN Red List of Threatened Species. IUCN, Gland, Switzerland.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson, and C. S. Holling. 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. Annual Review of Ecology, Evolution, and Systematics **35**:557-581.

Foster, G. and S. Rahmstorf. 2011. Global Temperature Evolution 1979–2010. Environmental Research Letters **6**:044022.

Francis, J. A. and S. J. Vavrus. 2012. Evidence Linking Arctic Amplification to Extreme Weather in Mid-Latitudes. Geophysical Research Letters **39**:L06801.

Friggens, Megan M., Deborah M. Finch, Karen E. Bagne, Sharon J. Coe, and David L. Hawksworth; 2013; Vulnerability of Species to Climate Change in the Southwest: Terrestrial Species of the Middle Rio Grande; United States Department of Agriculture, Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-306; July 2013.

Frenzel, P. F. 1995. Geohydrology and Simulation of Groundwater Flow Near Los Alamos, North-Central New Mexico. U.S. Geological Survey Water Resources Investigations Report 95-4091, Albuquerque.

Fritze, H., I. T. Stewart, and E. Pebesma. 2011. Shifts in Western North American Snowmelt Runoff Regimes for the Recent Warm Decades. Journal of Hydrometeorology **12**:989-1006.

Fu, Q. and P. Lin. 2011. Poleward Shift of Subtropical Jets Inferred from Satellite-Observed Lower-Stratospheric Temperatures. Journal of Climate **24**:5597-5603.

Gangopadhyay, S. and B. Harding. 2008. Stochastic Streamflow Simulations for the Otowi Gage. Memo to Dr. Nabil Shafike, P. E., New Mexico Interstate Stream Comission. Boulder: AMEC Earth & Environmental.

Garfin, G., editor. 2013. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. NCA Regional Input Reports. Island Press, Washington, D.C.

Gleick, P. H. 2000. Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. The Report of the Water Sector Assessment Team for the National Assessment on the Potential Consequences of Climate Variability and Change for the Water Resources of the United States for the U.S. Global Change Research Team.

Glick, P., B. A. Stein, and N. A. Edelson, editors. 2011. Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment. National Wildlife Federation, Washington, D.C.

Grantz, K., B. Rajagopalan, M. Clark, and E. Zagona. 2007. Seasonal Shifts in the North American Monsoon. Journal of Climate **20**:1923-1935.

Gutzler, D. S. 2000. Covariability of Spring Snowpack and Summer Rainfall Across the Southwest United States. Journal of Climate **13**:4018-4027.

______. 2003. Drought in New Mexico: History, Causes and Future Prospects. Pages 101-105 *in* P. S. Johnson, L. A. Land, L. G. Price, and F. Titus, editors. Water Resources of the Lower Pecos Region, New Mexico—Science, Policy, and a Look to the Future Decision-Makers Field Guide New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Gutzler, D. S., G. Garfin, and B. Zak. 2006. Observed and Predicted Impacts of Climate Change on New Mexico's Water Supplies. Pages 4-32 *in* A. Watkins, editor. The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources. New Mexico Office of the State Engineer/Interstate Stream Commission, Santa Fe, New Mexico.

Hargreaves, G. H., & Samani, Z. A. (1985). Reference Crop Evapotranspiration from Temperature. Applied Engineering in Agriculture, 96-99.

Harris, S. 2013. Personal Communication from Steve Harris, owner of Far Flung Adventures, June 2013.

Helsel, D. R. and L. M. Frans. 2006. The Regional Kendall Test for Trend. Environmental Science and Technology **40**:4066-4073.

Hidalgo, H. G., T. Das, M. D. Dettinger, D. R. Cayan, D. W. Pierce, T. P. Barnett, G. Bala, A. Mirin, A. W. Wood, C. Bonfils, B. D. Santer, and T. Nozawa. 2009. Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States. Journal of Climate **22**:3838-3855.

Hirsch, R. M. and K. R. Ryberg. 2011. Has the Magnitude of Floods Across the USA Changed with Global CO2 levels? Hydrological Sciences Journal **57**:1-9.

Hoerling, M. P., M. D. Dettinger, K. Wolter, J. Lukas, J. Eischeid, R. Nemani, B. Liebmann, and K. E. Kunkel. 2013. Evolving Weather and Climate Conditions of the Southwest United States. Page 509 *in* G. Garfin, editor. Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. NCA Regional Input Reports. Island Press, Washington, D.C.

Hurd, B. H. and J. Coonrod. 2007. Climate Change and its Implications for New Mexico's Water Resources and Economic Opportunities. New Mexico State University, Agricultural Experiment Station Technical Report 45, Las Cruces, New Mexico.

Interagency Climate Change Adaptation Task Force (ICCATF). 2011. National Action Plan Priorities for Managing Freshwater Resources in a Changing Climate. Washington, D.C.

Intergovernmental Panel on Climate Change (IPCC). 2000. Special Report on Emissions Scenarios. Page 599 *in* N. Nakicenovic and R. Swart, editors. Cambridge University Press. Cambridge, United Kingdom. Online: http://www.grida.no/climate/ipcc/emission/.

IPCC 2007 [Summary],2000. Summary for Policymakers: Emissions Scenarios. ISBN: 92-9169-113-5. Online: *https://www.**ipcc**.ch/pdf/**special-reports**/spm/sres-en.pdf*. Accessed 9/20/2013.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY.

Jin-Yi, Y. and Z. Yuhao. 2013. The Enhanced Drying Effect of Central-Pacific El Niño on US Winter. Environmental Research Letters **8**:014019.

Jones, C. 2002. The Administration of the Middle Rio Grande Basin, 1956-2002. Natural Resources Journal **42**:939-968.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in Snowfall Versus Rainfall in the Western United States. Journal of Climate **19**:4545-4559.

Kunkel, K. E., T. R. Karl, D. R. Easterling, K. Redmond, J. Young, X. Yin, and P. Hennon. 2013a. Probable Maximum Precipitation and Climate Change. Geophysical Research Letters **40**:1402-1408.

Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K. T. Redmond, and J. G. Dobson. 2013b. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. NOAA Technical Report NESDIS 142-5.

Lagasse, P.F. 1980. An Assessment of the Response of the Rio Grande to Dam Construction – Cochiti to Isleta Reach. Technical Report for United States Army Corps of Engineers, Albuquerque District, Albuquerque, New Mexico.

Leung, L. R., Y. Qian, X. Bian, W. M. Washington, J. Han, and J. O. Roads. 2004. Mid-Century Ensemble Regional Climate Change Scenarios for the Western United States. Climatic Change **62**:75-113.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models. Journal of Geophysical Research **99**(D7):14415–14428.

Liang X., E. F. Wood, and D. P. Lettenmaier. 1996. Surface Soil Moisture Parameterization of the VIC-2L Model: Evaluation and Modifications. Global Planet Change **13**: 195-206.

Lohmann, D., R. Nolte-Holube, and E. Raschke. 1996. A Large-Scale Horizontal Routing Model to be Coupled to Land Surface Parameterization Schemes. Tellus **48A**:708–72.

Lu, J., G. A. Vecchi, and T. Reichler. 2007. Expansion of the Hadley Cell Under Global Warming. Geophysical Research Letters **34**:L06805.

Lukas, J. 2008. The Long View of the Rio: What Tree Rings Tell Us About the Past Variability of the Rio Grande, and What it Means for our Future. Presented to the AWRA-NM Chapter, June 2, 2008. University of Colorado and Western Water Assessment.

Lundquist, J. D. and D. R. Cayan. 2007. Surface Temperature Patterns in Complex Terrain: Daily Variations and Long-Term Change in the Central Sierra Nevada, California. J. Geophys. Res. **112**:D11124.

MacDonald, G. M. 2010. Water, Climate Change, and Sustainability in the Southwest. Proceedings of the National Academy of Sciences of the United States of America **107**:21256-21262.

MacDonald, G. M., D. W. Stahle, J. V. Diaz, N. Beer, S. J. Busby, J. Cerano-Paredes, J. E. Cole, E. R. Cook, G. Endfield, G. Gutierrez-Garcia, B. Hall, V. Magana, D. M. Meko, M. Ménendez-Pérez, D. J. Sauchyn, E. Watson, and C. A. Woodhouse. 2008. Climate Warming and 21st Century Drought in Southwestern North America. EOS Transactions **89**:82-83.

Maidment, D. R., editor. 1993. Handbook of Hydrology. McGraw-Hill, New York City, New York.

Makar, P., T. Massong, and T. Bauer, 2006. Channel Width and Flow Regime Changes along the Middle Rio Grande, New Mexico, Joint 8th Federal Interagency Sedimentation Conference and 3rd Federal Interagency Hydrologic Modeling Conference, Reno, Nevada.

Mann, M. E., Z. H. Zhang, M. K. Hughes, R. S. Bradley, S. K. Miller, S. Rutherford, and F. B. Ni. 2008. Proxy-based Reconstructions of Hemispheric and Global Surface Temperature Variations Over the Past Two Millennia. Proceedings of the National Academy of Sciences of the United States of America **105**:13252-13257.

Mantua, N. 2013. PDO Index. Online: http://jisao.washington.edu/pdo/PDO.latest. Accessed March 21, 2013.

Marchetto, A. 2012. Package 'rkt': Mann-Kendall Test, Seasonal and Regional Kendall tests. R-project. Online: http://cran.r-project.org/web/packages/rkt/index.html. Accessed March 11, 2013.

Marcott, S. A., J. D. Shakun, P. U. Clark, and A. C. Mix. 2013. A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. Science **339**:1198-1201.

Maurer, E. P. 2007. Uncertainty in Hydrologic Impacts of Climate Change in the Sierra Nevada, California Under Two Emissions Scenarios. Climatic Change **82**:309–325.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen. 2002. A long-term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States. Journal of Climate **15**:3237-3251.

McAda, D. P. and P. Barroll. 2002. Simulation of Ground-Water Flow in the Middle Rio Grande Between Cochiti and San Acacia, New Mexico. U.S. Geological Survey, Albuquerque.

McAfee, S. A. and J. L. Russell. 2008. Northern Annular Mode Impact on Spring Climate in the Western United States. Geophysical Research Letters **35**.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt. 2004. Pacific and Atlantic Ocean Influence on Multidecadal Drought Frequency in the United States. Proceedings of the National Academy of Sciences of the United States of America **101**:4136-4141.

McCabe, G. J. and D. M. Wolock. 2009. Recent Declines in Western U.S. Snowpack in the Context of Twentieth-Century Climate Variability. Earth Interactions **13**:1-15.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell. 2007. The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research. Bulletin of the American Meteorological Society **88**:1383-1394.

Meko, D. M., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer. 2007. Medieval Drought in the Upper Colorado River Basin. Geophysical Research Letters **34**.

Mix, K., V. Lopes, and W. Rast. 2012. Growing Season Expansion and Related Changes in Monthly Temperature and Growing Degree Days in the Inter-Montane Desert of the San Luis Valley, Colorado. Climatic Change **114**:723-744.

Molotch, N. P. and R. C. Bales. 2006. SNOTEL Representativeness in the Rio Grande Headwaters on the Basis of Physiographics and Remotely Sense Snow Cover Persistence. Hydrologic Preocesses **20**:723-739.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining Mountain Snowpack in Western North America. Bulletin of the American Meteorological Society **86**:39-+.

Munson, S. M., J. Belnap, and G. S. Okin. 2011. Responses of Wind Erosion to Climate-Induced Vegetation Changes on the Colorado Plateau. Proceedings of the National Academy of Sciences of the United States of America **108**:3854-3859.

Nash, L. L. and P. H. Gleick. 1993. The Colorado River Basin and Climatic Change: the Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation. U.S. Environmental Protection Agency EPA230-R-93-009.

National Aeronautics and Space Administration. Nd. NASA's Remote Sensing Tutorial: The Water Planet - Meteorological, Oceanographic and Hydrologic Applications of Remote Sensing. https://www.fas.org/irp/imint/docs/rst/Sect14/Sect14_1c.html

National Center for Atmospheric Research (NCAR). 2012. Atlantic Multidecadal Oscillation (AMO). Online: http://www.cgd.ucar.edu/cas/catalog/climind/AMO.html. Accessed 28 March 2013.

National Drought Mitigation Center. 2013. U.S. Drought Monitor: West March 26, 2013. University of Nebraska-Lincoln. Online: http://droughtmonitor.unl.edu/DM_west.htm. Accessed 28 March 2013.

National Weather Service. 2011. El Niño/Southern Oscillation (ENSO) Diagnostic Discussion. http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/(Accessed March 16, 2011).

New Mexico Office of the State Engineer, editor. 2006. The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources. New Mexico Office of the State Engineer/Interstate Stream Commission, Santa Fe, New Mexico.

Nijssen, B., D. P. Lettenmaier, X. Liang, S. W. Wetzel, and E F. Wood. 1997. Streamflow Simulation for Continental-Scale River Basins. Journal of Water Resources Research **33**: 711–724.

NOAA. 2011a. 2010 Tied for Warmest Year on Record.

______. 2011b. National Weather Service Climate Prediction Center, Cold and Warm Episodes by Season.

______. 2013a. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 5. Climate of the Southwest U.S., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C.

______. 2013b. U.S. Seasonal Drought Outlook, Drought Tendency During the Valid Period, Valid for March 21-June 30, 2013. National Oceanic and Atmospheric Administration. Online: http://www.cpc.ncep.noaa.gov/products/expert_assessment/seasonal_drought.html. Accessed 28 March 2013.

NOAA National Climate Data Center. 2013. NCDC Announces Warmest Year on Record for Contiguous U.S. Online: http://www.ncdc.noaa.gov/news/ncdc-announces-warmest-year-record-contiguous-us. Accessed 27 March 2013.

Nydick, K., J. Crawford, M. Bidwell, C. Livensperger, I. Rangwala, and K. Cozetto. 2012. Climate Change Assessment for the San Juan Mountain Regions, Southwestern Colorado, USA: A Review of Scientific Research. Prepared by Mountain Studies Institute in Cooperation with USDA San Juan National Forest Service and USDOI Bureau of Land Management Tres Rios Field Office. Durango, CO. Online: <http://www.mountainstudies.org>.

Odum, E. P. 1953. Fundamentals of Ecology. W.B. Saunders, Philadelphia.

Payne, J. T., A. W. Wood, A. F. Hamlet, R. N. Palmer, and D. P. Lettenmaier. 2004. Mitigating the Effects of Climate Change on the Water Resources of the Columbia River basin. Climatic Change **62**(1–3):233–256.

Pederson, G. T., S. T. Gray, C. A. Woodhouse, J. L. Betancourt, D. B. Fagre, J. S. Littell, E. Watson, B. H. Luckman, and L. J. Graumlich. 2011. The Unusual Nature of Recent Snowpack Declines in the North American Cordillera. Science **333**:332-335.

Pepin, N. C., M. Losleben, M. Hartman, and K. Chowanski. 2005. A Comparison of SNOTEL and GHCN/CRU Surface Temperatures with Free-Air Temperatures at High Elevations in the Western United States: Data Compatibility and Trends. Journal of Climate **18**:1967-1985.

Plog, S. 1997. Ancient Peoples of the American Southwest. Thames and Hudson, London.

Porinchu, D. F., G. M. MacDonald, K. A. Moser, and A. M. Bloom. 2005. A Quantitative Midge-Based Reconstruction of Late Pleistocene-Early Holocene Temperatures in the Sierra Nevada, CA. MTNCLIM 2005: A Science Conference on Mountain Climates & Effects on Ecosystems. Consortium for Integrated Climate Research in Western Mountains (CIRMOUNT). Poster online: <athttp://www.fs.fed.us/psw/cirmount/meetings/mtnclim/2005/talks/Porinchu_poster.pdf>. Accessed April 4, 2013., Pray, Montana.

Rahmstorf, S., G. Foster, and A. Cazenave. 2012. Comparing Climate Projections to Observations up to 2011. Environmental Research Letters **7**:044035.

Rango, A. and J. Martinec. 2008. Predictions for Snow Cover, Glaciers and Runoff in a Changing Climate.*in* HydroPredict 2008, Prague, Czech Republic, 15-18 September 2008.

Rangwala, I. 2012. Amplified Water Vapour Feedback at High Altitudes During Winter. International Journal of Climatology:n/a-n/a.

Rangwala, I. and J. R. Miller. 2010. Twentieth Century Temperature Trends in Colorado's San Juan Mountains. Arctic Antarctic and Alpine Research **42**:89-97.

Ray, A. J., J. J. Barsugli, K. B. Averyt, K. Wolter, M. Moerling, N. Doesken, B. Udall, and R. S. Webb. 2008. Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. A Report for the Colorado Water Conservation Board, Boulder, Colorado.

Reclamation. 1964. San Juan - Chama Project Definite Plan Report. Southwest Region, Amarillo, Texas.

______. 1986. San Juan - Chama Project Yield Update. Southwest Region, Amarillo, Texas.

______. 1989. San Juan - Chama Project Yield Update Addendum to the 1986 Study. Southwest Region, Amarillo, Texas.

______. 1999. Revised San Juan-Chama Firm Yield (Draft). Upper Colorado Region, Albuquerque, New Mexico.

______. 2011a. SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water Report to Congress. 2011. U.S. Department of the Interior, Bureau of Reclamation, Office of Policy and Administration, Denver, Colorado.

______. 2011b. Upper Colorado Region.

______. 2011c. West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections. U. S. Department of the Interior, Bureau of Reclamation Technical Memorandum No. 86-68210-2011-01, Denver, Colorado.

Roach, J. D. 2009. Stochastic Hydrologic Analysis of the Upper Rio Grande Surface Water System in New Mexico. Report to the U.S. Bureau of Reclamation.

Rocky Mountain Climate Organization (RMCO). 2005. April 1st Snowpacks Compared to Historical Averages. Data from the Natural Resources Conservation Service.

Saunders, S. and M. Maxwell. 2005. Less Snow, Less Water: Climate Disruption in the West. Louisville, CO.

Scurlock, Dan 1998. From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin. General Technical Report RMRS-GTR-5. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Fort Collins, Colorado.

Seager, R. and N. Naik. 2012. A Mechanisms-Based Approach to Detecting Recent Anthropogenic Hydroclimate Change. Journal of Climate **25**:236-261.

Seager, R., M. F. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H. P. Huang, N. Harnik, A. Leetmaa, N. C. Lau, C. H. Li, J. Velez, and N. Naik. 2007. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. Science **316**:1181-1184.

Seager, R. and G. A. Vecchi. 2010. Greenhouse Warming and the 21st Century Hydroclimate of Southwestern North America. Proceedings of the National Academy of Sciences of the United States of America **107**:21277-21282.

Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler. 2008. Widening of the Tropical Belt in a Changing Climate. Nature Geoscience **1**:21-24.

Serrat-Capdevila, A., J. Valdes, J. Gonzalez-Perez, K. Baird, L. J. Mata, and T. I. Maddock. 2007. Modeling Climate Change Impacts – and Uncertainty – on the Hydrology of a Riparian System: the San Pedro Basin (Arizona/Sonora). Journal of Hydrology **347**:48-66.

Service. See U.S. Fish and Wildlife Service.

Seth, A., S. A. Rauscher, M. Rojas, A. Giannini, and S. J. Camargo. 2011. Enhanced Spring Convective Barrier for Monsoons in a Warmer World? Climatic Change **104**:403-414.

Shafike, N.G. 2007. Linked Surface Water and Groundwater Model for Socorro and San Marcial Basins between San Acacia and Elephant Butte Reservoir. Rio Grande Water Operations Review DEIS. Albuquerque.

Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The Climate of the US Southwest. Climate Research **21**:219-238.

S. S. Papadopulos & Associates. 2000. Middle Rio Grande Water Supply Study. Boulder, Colorado.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2004. Changes in Snowmelt Runoff Timing in Western North America Under a 'Business as Usual' Climate Change Scenario. Climatic Change **62**:217-232.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes Toward Earlier Streamflow Timing Across Western North America. Journal of Climate **18**:1136-1155.

Swetnam, T. W. and J. L. Betancourt. 1998. Mesoscale Disturbance and Ecological Response to Decadal Climatic Variability in the American Southwest. Journal of Climate **11**:3128-3147.

Tebaldi, C., D. Adams-Smith, and N. Heller. 2012. The Heat is On: U.S. Temperature Trends. Palo Alto, California.

U.S. Army Corps of Engineers (USACE). 2007.

U.S. Bureau of Reclamation. See Reclamation.

U.S. Census Bureau. 2010. City, County, and State Population Estimates for New Mexico, 2010. http://www.census.gov

U.S. Environmental Protection Agency (EPA). 2013. Draft Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient, and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds. EPA/600/R-12/058A.

U.S. Fish and Wildlife Service (FWS). 2003. Biological and Conference Opinions of the Effects of Actions Associated with the Programmatic Biological Assessment of Bureau of Reclamation's Water and River Maintenance Operations, Army Corps of Engineers' Flood Control Operation, and Related Non-Federal Actions on the Middle Rio Grande, New Mexico. Cons. #2-22-03-F-0129 Dated March 17, 2003. FWS P.O. Box 1306, Albuquerque, New Mexico, 87103-1306.

______. 2005. Designation of critical habitat for the Southwestern Willow Flycatcher (*Empidonax traillii extimus*), Final Rule, October 19, 2005. Federal Register **70**:60886-61009.

U.S. Global Change Research Program (USGCRP). 2009. Global Climate Change Impacts in the United States. Cambridge University Press, Cambridge, United Kingdom.

______. 2013. Draft Third National Climate Assessment Report.

University of Arizona, the Western Regional Climate Center/Desert Research Institute, and the PRISM Climate Group at Oregon State University. 2007. Climate Analysis & Mapping Toolbox. Online: <http://www.cefa.dri.edu/Westmap/Westmap_home.php>

Veatch, W., P. D. Brooks, J. R. Gustafson, and N. P. Molotch. 2009. Quantifying the Effects of Forest Canopy Cover on Net Snow Accumulation at a Continental, Mid-Latitude Site. Ecohydrology **2**:115-128.

Vecchi, G. A. and A. T. Wittenberg. 2010. El Nino and Our Future Climate: Where do We Stand? Wiley Interdisciplinary Reviews-Climate Change **1**:260-270.

Walker, B. and J. A. Meyers. 2004. Thresholds in Ecological and Social–Ecological Systems: A Developing Database. Ecology and Society **9**:3. Online: http://www.ecologyandsociety.org/vol9/iss2/art3/.

Wehner, M., D. R. Easterling, J. H. Lawrimore, R. R. Heim, R. S. Vose, and B. D. Santer. 2011. Projections of Future Drought in the Continental United States and Mexico. Journal of Hydrometeorology **12**:1359-1377.

Wigmosta, M. S., L. W. Vail, and D. P. Lettenmaier. 1994. A Distributed Hydrology Vegetation Model for Complex Terrain. Water Resources Research **30**: 1665-1679.

Williams, A. P., C. D. Allen, C. I. Millar, T. W. Swetnam, J. Michaelsen, C. J. Still, and S. W. Leavitt. 2010. Forest Responses to Increasing Aridity and Warmth in the Southwestern United States. Proceedings of the National Academy of Sciences.

Willows, R. I. and R. K. Connell, editors. 2003. Climate Adaptation: Risk, Uncertainty and Decision-Making. UKCIP Technical Report, Oxford, United Kingdom.

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier. 2004. Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. Climatic Change **15**: 189-216.

Woodhouse, C. A., D. M. Meko, G. M. MacDonald, D. W. Stahle, and E. R. Cooke. 2010. A 1,200-Year Perspective of 21st Century Drought in Southwestern North America. Proceedings of the National Academy of Sciences of the United States of America 107:21283-21288.

Woodhouse, C. A., D. W. Stahle, and J. Villanueva-D ıaz (2012), Rio Grande and Rio Conchos water supply variability over the past 500 years, Climate Resources 51, 147–158, doi:10.3354/cr01059.Online: http://treeflow.info/riogr/riograndedelnorte.html#reconstruction. Accessed 9/20/2013.

Appendices

A Upper Rio Grande System and Operations

B Literature Review of Observed and Projected Climatic Changes

C Observed Climate Trends in the Upper Rio Grande Basin

D Development of Hydro Projections

E The Upper Rio Grande Simulation Model (URGSiM)

F References Cited

Appendix A

Upper Rio Grande System and Operations

Appendix B

Literature Review of Observed and Projected Climate Changes

Appendix C

Observed Climate Trends in the Upper Rio Grande Basin

Appendix D

Development of Hydro Projections

Appendix E

The Upper Rio Grande Simulation Model (URGSiM)