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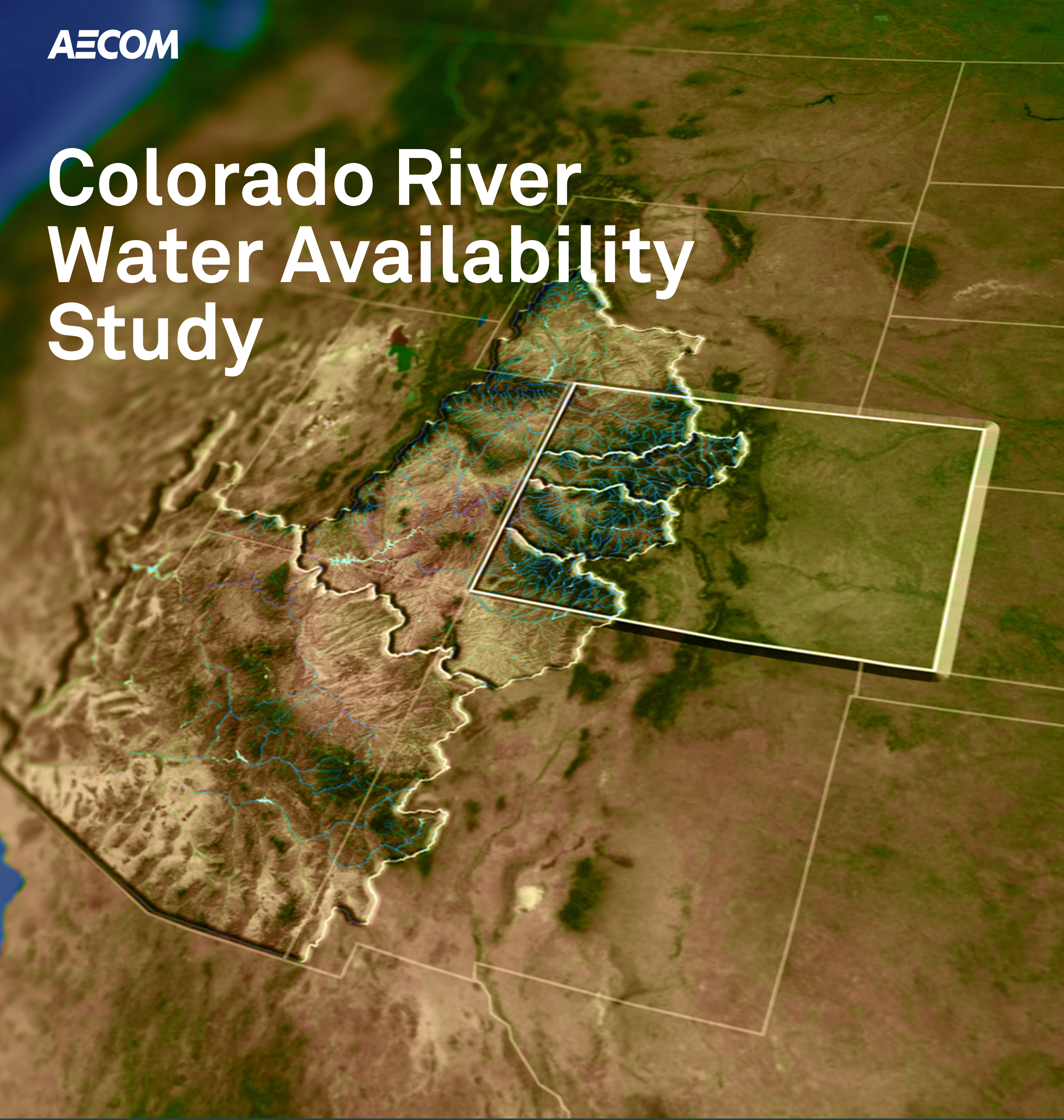
Colorado River Water Availability Study



Colorado Water Conservation Board
Colorado River Water Availability Study
Phase I Report

In Association with
AMEC Earth & Environmental
Canyon Water Resources
Leonard Rice Engineers, Inc.
Stratus Consulting

March 2012

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

SUPPORTING MATERIAL

CRWAS Project Documents

Phase I of the CRWAS includes a series of interim documents covering a wide range of topics to support development of this report. These interim documents include the CRWAS Phase I Scope of Work, Technical Memoranda, Modeling Briefs, Presentations, and Newsletters. They are available on the CWCB website (http://cwcb.state.co.us) for readers interested in more detailed information on Study background, technical approach, and results.

CRWAS Comment / Response Matrix

The CWCB and CRWAS team greatly appreciates the consideration, communication, and comments provided by multiple entities during their review of the March 22, 2010 Draft CRWAS Phase I Report. The written comments received during the Study's public review period (March 22, 2010 – July 21, 2010) were reviewed and considered by the CRWAS team to guide refinements of the work and to provide stakeholders with a better understanding of the Study. Public comment letters and the corresponding public comment / response matrix associated with the Draft CRWAS Phase I Report are available on the CWCB website (http://cwcb.state.co.us).

CRWAS is based on the best data, science, techniques, and tools that are reasonably available and useful to meet Study objectives. The Study presents a valuable body of knowledge for stakeholders and State agencies for on-going water planning and management activities. The CWCB is continuing its public and stakeholder outreach meetings and workshops, refinements to its computer models and analyses, and consideration of future CRWAS activities.

CRWAS Data Viewer

A large portion of the CRWAS work was based on water resources modeling using tools in the Colorado Decision Support System (CDSS), including its surface water model, StateMod. The standard utility for working with StateMod data, TSTool, is the most appropriate tool for performing analysis with model output and extracting modeling time series input. However, TSTool requires a significant learning curve for efficient use. It became clear through public input that Colorado water stakeholders would benefit from a more user-friendly CRWAS data viewing tool. Therefore, the CRWAS team developed the "CRWAS Data Viewer" to provide an interface to view and download CRWAS StateMod results. The CRWAS Data Viewer is a simple alternative for:

- Exploring CRWAS model locations on an interactive Google Map,
- Quickly comparing data from different CRWAS modeled scenarios,
- Comparing CRWAS data for user-selected locations, parameters, and scenarios,
- Downloading a subset of CRWAS model data.

The CRWAS Data Viewer may be used from any computer with an internet connection and a modern browser (released 2010 or later), without the need to download and learn new software. The CRWAS Data Viewer (and corresponding User Manual) is available on the CWCB website (http://cwcb.state.co.us).

CDSS Model Documentation

The CRWAS was able to take full advantage of the previous development of CDSS modeling tools (e.g., StateMod and StateCU). The extensive CRWAS public outreach through Basin Roundtable (BRT) meetings, IBCC meetings, and modeling workshops also provided an opportunity to enhance the existing model data sets for the CDSS. CDSS background and development activities are described in multiple documents including:

- CWCB website (http://cwcb.state.co.us)
  - CRWAS Task 4.1 Technical Memorandum – Overview of the CDSS / Modeling Briefs
  - CRWAS Task 4.4 Technical Memorandum – Recommended Model Refinements
- CDSS website (http://cdss.state.co.us/)
  - StateMod and StateCU Basin Information Reports and User Manuals

Acronyms

AF	Acre Feet
AG	Attorney General
ASCE	American Society of Civil Engineers
BRT	Basin Roundtables
CCTAG	Climate Change Technical Advisory Group
CDSS	Colorado Decision Support System
CIR	Crop Irrigation Requirement
CRDSS	Colorado River Decision Support System
CRSP	Colorado River Storage Project
CRSS	Colorado River Simulation System
CRWAS	Colorado River Water Availability Study
CWCB	Colorado Water Conservation Board
CWRRI	Colorado Water Resources Research Institute
DMI	Data Management Interface
DNR	Department of Natural Resources
DWR	Division of Water Resources
ET	Evapotranspiration
GAO	Government Accountability Office
GCM	Global Climate Model (also General Circulation Model)
GHG	Greenhouse Gas
HydroBase	State of Colorado's Relational Database
IBCC	Interbasin Compact Committee
IPCC	Intergovernmental Panel on Climate Change
IPPs	Identified Projects and Programs
JFRCCVS	Joint Front Range Climate Change Vulnerability Study
LLNL	Lawrence Livermore National Laboratory
M&I	Municipal and Industrial
MAF	Million Acre Feet

MLR	Multiple Linear Regression
NHMC	Non-Homogeneous Markov Chain
NOAA	National Oceanic and Atmospheric Administration
PC	Principal Component
RISA	Regional Integrated Sciences and Assessments
RMRS	Rocky Mountain Research Station
SCS	Soil Conservation Service
SCU	Santa Clara University
SRES	Special Report on Emissions Scenarios
StateCU	State of Colorado's Consumptive Use Model
StateMod	State of Colorado's Stream Simulation Model
TR-21	Technical Release 21
TSTool	Time Series Tool
UCRC	Upper Colorado River Commission
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity (Model)
WCRP	World Climate Research Program
WWA	Western Water Assessment

Where to find more detailed information:

A glossary of standard terms related to water resources, water rights, paleohydrology, and climate change topics is provided in CRWAS Task 3.1 – *Glossary of Terms*, available at: http://cwcb.state.co.us.

ACKNOWLEDGEMENTS

Phase I of the CRWAS involved extensive collaboration to share the Study's technical approaches, to participate in related programs, and to receive feedback on Study results. These activities enhanced statewide dialogue and foster understanding of the Study. CRWAS outreach activities were closely coordinated with the public communication programs of the CWCB Water Supply Planning Section and on-going State-sponsored IBCC processes. Interested stakeholders helped refine the State's water resources modeling tools. The additional hydrologic data and operational expertise they provided help assure that the State's systems have credibility with all types of water users and stakeholders. The Study outreach process facilitated by the State demonstrated its collaborative and transparent approach to water management.

The rapidly evolving science and practice of climate change assessments warrants collaboration and participation with other organizations focusing on potential climate change impacts to water resources. Many of these organizations made staff available through the State's Climate Change Technical Advisory Group (CCTAG) and these individuals provided considerable input on the Study's technical approaches.

The CRWAS study team is comprised of the following lead team members: Blaine Dwyer (AECOM – project management and technical review), Ben Harding (AMEC – paleohydrology, climate change, and compact implications), Erin Wilson and Matt Brown (Leonard Rice Engineers, Inc. water allocation modeling and project coordination), Jim Pearce (Canyon Water Resources – forest change assessment), and Joel Smith (Stratus Consulting – climate change).

The study team thanks the following individuals and groups for their support of the Study and collaboration with the CRWAS study team:

- Senator Isgar and Representative Curry – sponsors of the legislation authorizing the Study
- Colorado Governor – John Hickenlooper
- Colorado Water Conservation Board (CWCB)
    - Appointed Board Members
        - Alan Hamel (Arkansas River)
        - Russ George (Colorado River Mainstem)
        - Barbara Biggs (City & County of Denver)
        - John H. McClow (Gunnison-Uncompahgre River)
        - Carl Trick II (North Platte River)
        - Travis Smith (Rio Grande River)
        - April Montgomery (San Miguel, Dolores, Animas & San Juan Rivers)
        - Eric Wilkinson, (South Platte River)
        - Geoff Blakeslee, (Yampa/White Rivers)
    - Ex-Officio Members
        - Mike King, Executive Director - Department of Natural Resources
        - John Salazar, Commissioner - Department of Agriculture
        - Jennifer Gimbel, Director - CWCB
        - Rick Cables, Director - Division of Parks and Wildlife

        - Dick Wolfe, State Engineer - Division of Water Resources
        - John Suthers, Attorney General
- IBCC Director of Compact Negotiations - John Stulp,
- CWCB Management – Jennifer Gimbel, Director
- CWCB CRWAS Study Manager – Ray Alvarado and consulting technical support – Ross Bethel
- Office of the Attorney General (AG) – Karen Kwon and Shanti Rosset O'Donovan
- Staff of the CWCB – All sections of the CWCB contributed to the CRWAS; in particular, the following individuals provided direction throughout the Study at progress meetings; facilitated IBCC, BRT, and public input; and reviewed work products:
    - Eric Hecox
    - Jacob Bornstein
    - Greg Johnson
    - Todd Doherty
    - Veva Deheza
    - Taryn Hutchins-Cabibi
    - Ted Kowalski
    - Michelle Garrison
    - Linda Bassi
    - Randy Seaholm (retired)
- CWCB CCTAG
- Interbasin Compact Committee (IBCC) and IBCC Basin Roundtables (BRTs)
- Joint Front Range Climate Change Vulnerability Study (JFRCCVS) Program
- NOAA Regional Integrated Sciences and Assessments (RISA) Program
- University of Colorado's Western Water Assessment (WWA) NOAA Program
- Colorado House-Senate Joint Agriculture Committee
- Northern Colorado Water Conservancy District
- Colorado River Water Conservation District
- Front Range Water Council
- Colorado Water Congress

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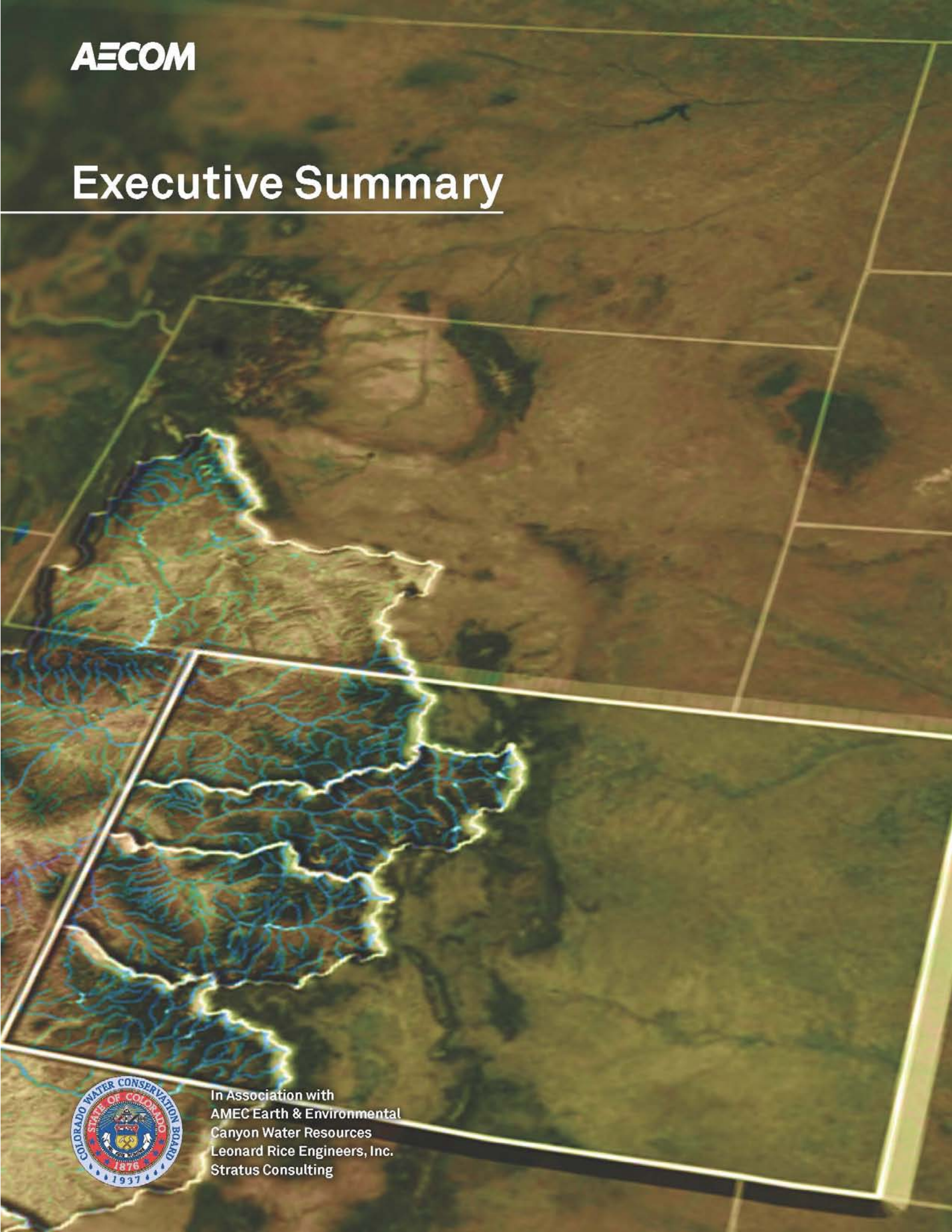
Executive Summary



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EXECUTIVE SUMMARY

Phase I of the Colorado River Water Availability Study (the Study or CRWAS) provides an unprecedented foundation for water resources planning in Colorado. The Study, which began in 2008, combines the data and models developed by the CWCB and the Division of Water Resources over the last 15 years with new information on past droughts and wet spells and possible future changes in climatic conditions to produce the most comprehensive look to date at the Colorado River water supply in our State. Phase I of the Study provides a strong foundation for subsequent work, which will examine water availability for future water supply projects and for additional non-consumptive water needs. The Study is guided by extensive public involvement and provides a transparent examination of complex water management issues and the data, science, and computer tools applied to assess these issues. With the publication of this report and the launch of the CRWAS on-line data viewer, Colorado's water community can now fully utilize this Phase I assessment of water availability for our current supply systems and levels of water demands. State agencies and Colorado River stakeholders can now prepare for further assessments of water management strategies to meet future demands and investigate the risks associated with each of them.

Background and Objectives

Study Authorization

Colorado faces increasing demands on its water supply for both traditional consumptive uses (such as agriculture, municipal, industrial, and commercial uses) and for non-consumptive uses (such as environmental and recreational needs). Population growth; recent drought; oil, gas, and mineral development; and potential climate change broaden our concerns about the adequacy of Colorado's water supplies. Responding to these concerns, the Colorado General Assembly authorized the CRWAS through Senate Bill (SB) 07-122 and House Bill (HB) 08-1346. These bills direct the CWCB to conduct the Study: (1) in collaboration with the Interbasin Compact Committee (IBCC) and the State's river BRTs, and (2) with consideration for current and potential future in-basin consumptive and non-consumptive needs. These two directives led to broad-based and transparent public input, expanding the discussion from traditional types of consumptive water use to encompass environmental, recreational, and aesthetic uses of water.

A Study Team led by AECOM and including AMEC Environment & Infrastructure, Canyon Water Resources, Leonard Rice Engineers, Inc., and Stratus Consulting began work in late 2008, leading to a first draft of this report in March 2010. Recognizing the importance and interest in the Study, the CWCB set a 4-month public comment period and conducted extensive additional public outreach and technical analysis to respond to the broad range of comments received. To date, more than 60 public presentations and workshops about the CRWAS have been held with various groups including the CWCB's Board of Directors, IBCC,Basin Roundtables (BRTs), Colorado Water Congress, and many others. The input and direction received from broad-ranging interests refined the focus and approach of the Study. It now provides more relevant and responsive information to Colorado water users, managers, policy makers, and stakeholders about current and potential future hydrologic conditions in the Colorado River tributaries that sustain our State's critical economic sectors and natural ecosystems. The Study is a source of useful water management information, but it is not intended to prescribe policies. Each organization, agency, and individual can interpret the Study results from its own perspective, considering its own assessment of the possible future conditions, its role in water management, the resources it has to adapt to alternative potential future conditions, and its tolerance for risk.

Study Phasing

Working closely with the IBCC, the CWCB is conducting the Study in multiple phases. Phase I (the subject of this report) is an assessment of water availability based on existing levels of water use (see Figure ES-1). For Phase I, the analysis of water availability focuses on current levels of water demands served by water rights now in use ("perfected" or "absolute" water rights). Phase I also focuses on interpretations of current operating and management practices for water diversion, storage, and conveyance facilities. For example, in scenarios where potential changes in climate conditions could affect the magnitude of water demands served by current water rights and irrigation systems, Phase I allows for the diversion of water up to the decreed maximum in the current water right. The difference between the crop's needs under new climate conditions and water diverted under the Phase I simulations is reported as a shortage.

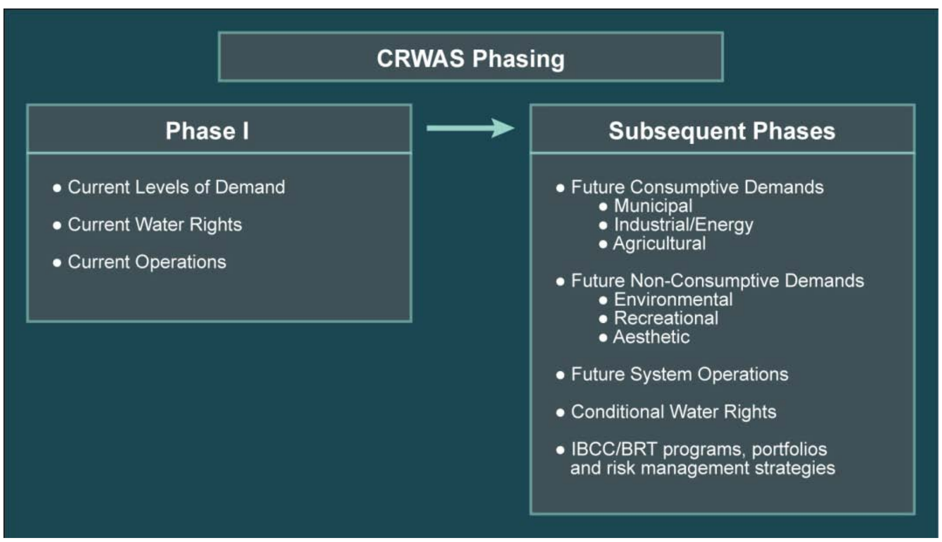


Figure ES-1 – CRWAS Phasing

The process of defining the potential future water demands , both consumptive and non-consumptive, that will be analyzed in subsequent phases of the CRWAS is currently underway through the State's IBCC processes coordinated by the CWCB. The primary focus of future phases will likely be to simulate the hydrologic effects of the various water demand scenarios, water supply portfolios, and potential changes to existing project operation. Subsequent phases will lay the foundation for individual or collective assessments of risk and potential strategies to manage or minimize risk. Regardless of the scope of future phases, the information, tools, and modeling results from Phase I will continue to support a broad range of CWCB programs and responsibilities, including continuing assessments of:

- Streamflows and reservoir storage to support water supply
- Flood protection and management
- Instream flow protection
- Water conservation
- Endangered species recovery
- Intra-state, interstate, and federal issues and programs

As shown in Figure ES-2, there are many ongoing programs and processes that the CWCB performs or directs in close collaboration with other State agencies and programs. In addition to other State, federal and local agencies, the CWCB is coordinating closely with the IBCC and BRTs in reviewing the Study's methods and results.

Figure ES-2 – State-Sponsored Water Management Programs Supported by the CRWAS

Study Area

The Study Area for the CRWAS encompasses the major tributary river basins of the Colorado River in the State of Colorado. Figure ES-3, presents the Study Area in accordance with the basins defined for the four West Slope BRTs. Elsewhere in this report, the basins comprising this Study Area are also referenced using the nomenclature of the Colorado Decision Support System (CDSS) for consistency in displaying modeling results. The CDSS consists of data and tools developed Statewide, plus models developed under basin-specific DSS efforts. The Colorado River DSS (CRDSS) models were developed for the Yampa, White, Upper Colorado, Gunnison, and San Juan/Dolores basins. The term CDSS is used throughout this document to refer to both the larger CDSS effort, and the basin-specific development.

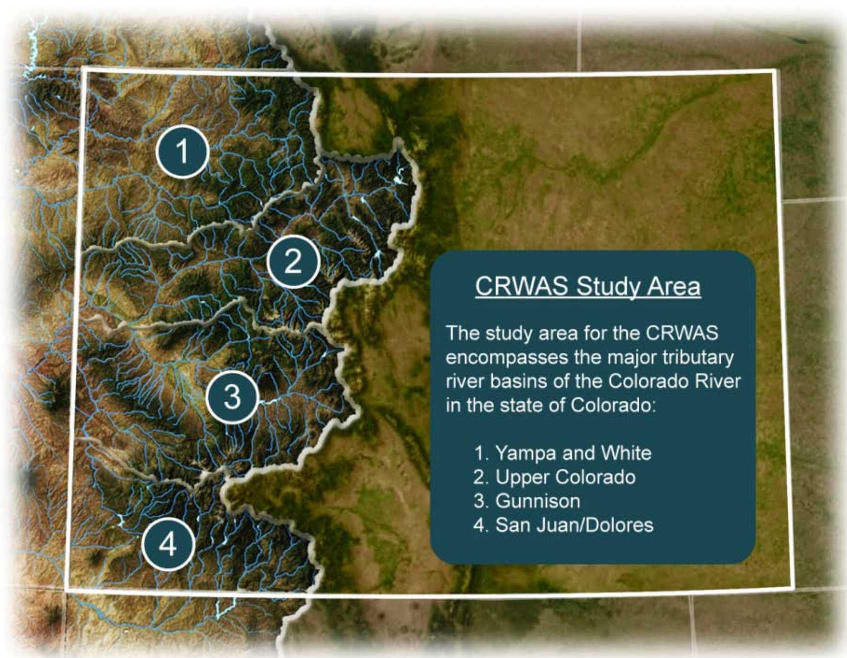


Figure ES-3 – CRWAS Study Area

Unique Attributes of the CRWAS

Studies considering the effects of climate change on water resources are being conducted world-wide; including two studies that have been completed, or are near completion, that cover a portion of the geographical area covered by the CRWAS. The Joint Front Range Climate Change Vulnerability Study (JFRCCVS), published in February 2012 by the Water Research Foundation, was undertaken to examine the potential effects that climate change may have on the supplies available to several Front Range municipal water agencies. The overlapping geographical area for the JFRCCVS and the CRWAS is the Colorado River main stem in Colorado and its tributaries. The U.S. Bureau of Reclamation is moving to finalize the Colorado River Basin Water Supply and Demand Study (CRBS) in the summer of 2012. This study completely encompasses the geographic area of the CRWAS and extends downstream to cover the entire Colorado River Basin. The primary purpose of the CRBS is to “define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin

States that receive Colorado River water over the next 50 years (through 2060), and to develop and evaluate adaptation and mitigation strategies to resolve those imbalances." Each of these studies inform stakeholders how water supplies may vary under changing climate conditions.

The JFRCCVS accomplished its goal of identifying changes to natural flow at 18 river locations for five climate projections representing 2040 and five representing 2070. As discussed in more detail in Section 2.3.4, the CRWAS investigated the same scenarios for 2040 but chose different projections for 2070 that better represented its study area. The JRCCVS scope did not include investigating how climate change may affect basin demands, nor did it investigate how climate change may affect future agricultural water consumption, affect water available to satisfy other specific water uses, or affect operations of existing water supply systems.

The CRBS identified changes to natural flow at 29 locations throughout the entire Colorado River basin reflecting estimated annual change through 2060, including locations in seven states, for all 112 available climate projections. They developed relationships based on degree increases in temperature and annual changes in precipitation to adjust their aggregated irrigation demands to reflect climate change. Finally, they used the Colorado River Simulation System (CRSS) model with the revised natural flows and demands to identify supply and demand imbalances in both the Upper Colorado and Lower Colorado river basins. Although the CRSS model does not include specific water rights or non-federal project operations in Colorado, it does represent the critical operations of Lake Powell and Lake Mead.

The State of Colorado has developed tools that allow the CRWAS to go well beyond both the JFRCCVS and the CRBS studies to investigate how climate change may affect water availability at the water user and water rights level, and how climate change may affect reservoir use and operations. The approach adopted by CRWAS may be the most detailed look at how specific water users may be impacted by climate change performed to-date anywhere in the world. This was made possible because of the availability of the CDSS model datasets previously developed for the Colorado River in Colorado. CDSS model datasets have not been fully developed for either the South Platte or the Arkansas River basins; therefore were not available for use in the JFRCCVS.

The existing CDSS consumptive use model (StateCU) datasets represent 100 percent of the current estimated irrigated acreage and irrigation practices at the ditch level. The existing CDSS water allocation model (StateMod) datasets represent the current water rights and administrative agreements, water user demands, and basin operations superimposed on natural flows throughout the Study Area. The availability of these datasets allowed the CRWAS to revise crop demands at the ditch level, using StateCU, to reflect current acreage and crop types and potential changes to growing seasons based on more locally estimated climate change parameters. Diversion demands, again at the ditch level, were adjusted to reflect crop demands. StateMod was then used to superimpose streamflows and climate-altered water use using Colorado's current water rights, administrative rules and agreements, and operational practices. The results provide detailed information on consumptive use; shortages; physical streamflow; and water available for future use at more than 2,000 locations throughout the Study Area. In addition, reservoir use (storage and releases) are provided for more than 60 federal and non-federal reservoirs throughout the Study Area.

Each of these three complementary studies help inform stakeholders how water supplies may vary under changing climate conditions. The JFRCCVS focuses on potential changes in natural flows that may affect Front Range municipal water providers and the CRBS focuses on potential changes in natural flows and federal reservoir operations throughout the seven-state Colorado River basin; The CRWAS includes effects on natural flow but extends the analysis to consider resulting changes in crop consumptive use, federal and non-federal reservoir operations and remaining water availability for consumptive and non-consumptive purposes.

Technical Approach

Water availability studies like the CRWAS compare water supply and demand based on the "supply-and-demand equation":

Water Available for Future Uses = Supply – Demand

Supplies and demands vary from day to day. They vary seasonally and they vary in dry years and wet years. Complex computer models are used to track the water supplies in streams and reservoirs and to reflect the actions of water managers as they operate supply systems to minimize shortages and as they deal with increasing competition for water among cities, industry, agriculture, recreation, and the environment. The flexibility of water managers to minimize shortages is constrained by the terms of their water rights, operation plans and water exchange agreements.

A primary challenge in conducting a comprehensive water availability study is developing the tools (computer models) needed to: (1) mimic natural phenomena as water flows through drainage basins, and (2) simulate the operations of stream diversion structures and reservoirs, and (3) represent flows returning to streams from cities, farms, and industry, - all operating under the umbrella of Colorado's Prior-Appropriation Doctrine. Fortunately for the CRWAS, the State of Colorado had the foresight to invest in the development of comprehensive computer tools over the past 15 years that allow this study to be performed with relative efficiency and in great detail. The CDSS, with its integrated databases and simulation models, is likely the most comprehensive, transparent, and geographically extensive system for water supply analyses available anywhere in the U.S.

The health of Colorado's forests is very important to regional ecological conditions that have potential effects on water supplies. Phase I of the CRWAS reviewed the practicality of modeling the hydrologic effects of recent and on-going changes in our forest lands as part of the Study's focus to assess long-term water supply availability.

The U.S. Forest Service (USFS), in conjunction with the CWCB and the North Platte River Basin Roundtable, is conducting a multi-year study to collect information regarding the forest change processes that most influence the hydrology of disturbed forests in Colorado. Given that the focus of Phase I of the CRWAS is to evaluate long-term water availability, it is appropriate to re-assess quantifying the impact of forest change on water availability when results of the USFS work are available and the science of forest change assessment is more advanced.

The March 2010 Draft CRWAS Phase I Report provided quantitative estimates of the amount of consumptive use, above existing levels, that can occur within Colorado under certain Colorado River Compact assumptions ("water available for future consumptive use"). After careful consideration, the Study Team and the CWCB agreed that the preliminary analyses of the March 2010 Draft Report would be replaced with a summary of the complexities, challenges, and uncertainties inherent in estimating the magnitude of water available for future consumptive uses in Colorado. This summary is presented in Section 2.2.6 of the main report.

Phase I of the CRWAS is composed of two primary analysis components: 1) CDSS Refinements and 2) Water Availability Assessments as follows.

Continuing CDSS Refinements

The CRWAS leveraged the State's investment in the Colorado Decision Support System (CDSS) modeling tools. Through extensive public outreach and direct collaboration with water suppliers and managers, the models were reviewed and refined to further enhance general confidence in the models' ability to simulate streamflows and project operations, and to provide important information for future assessments of non-consumptive water needs. The refinements were thoroughly documented to support subsequent CRWAS phases and other future State water resource modeling and planning initiatives. The CDSS proved fully capable of simulating current water uses (demands) and alternate hydrologic cases to provide a broad range of results including physical streamflow, consumptive use, and water available to meet future demands throughout the Study Area under Colorado's Prior Appropriation Doctrine.

Water Availability Assessments

Phase I considers and compares three different conditions for water supply:

1. **Historical Hydrology** – Traditionally, water supply agencies have used recorded historical information on water supply as an indication of likely future conditions, the premise being that history tends to repeat itself. This Study uses a 56-year period to represent historical hydrology (1950 through 2005). This period includes both very wet and very dry years, contains the most reliable historical data upon which to base comparisons of the effects of climate change, and uses information that Colorado River stakeholders can relate to through their own experiences.

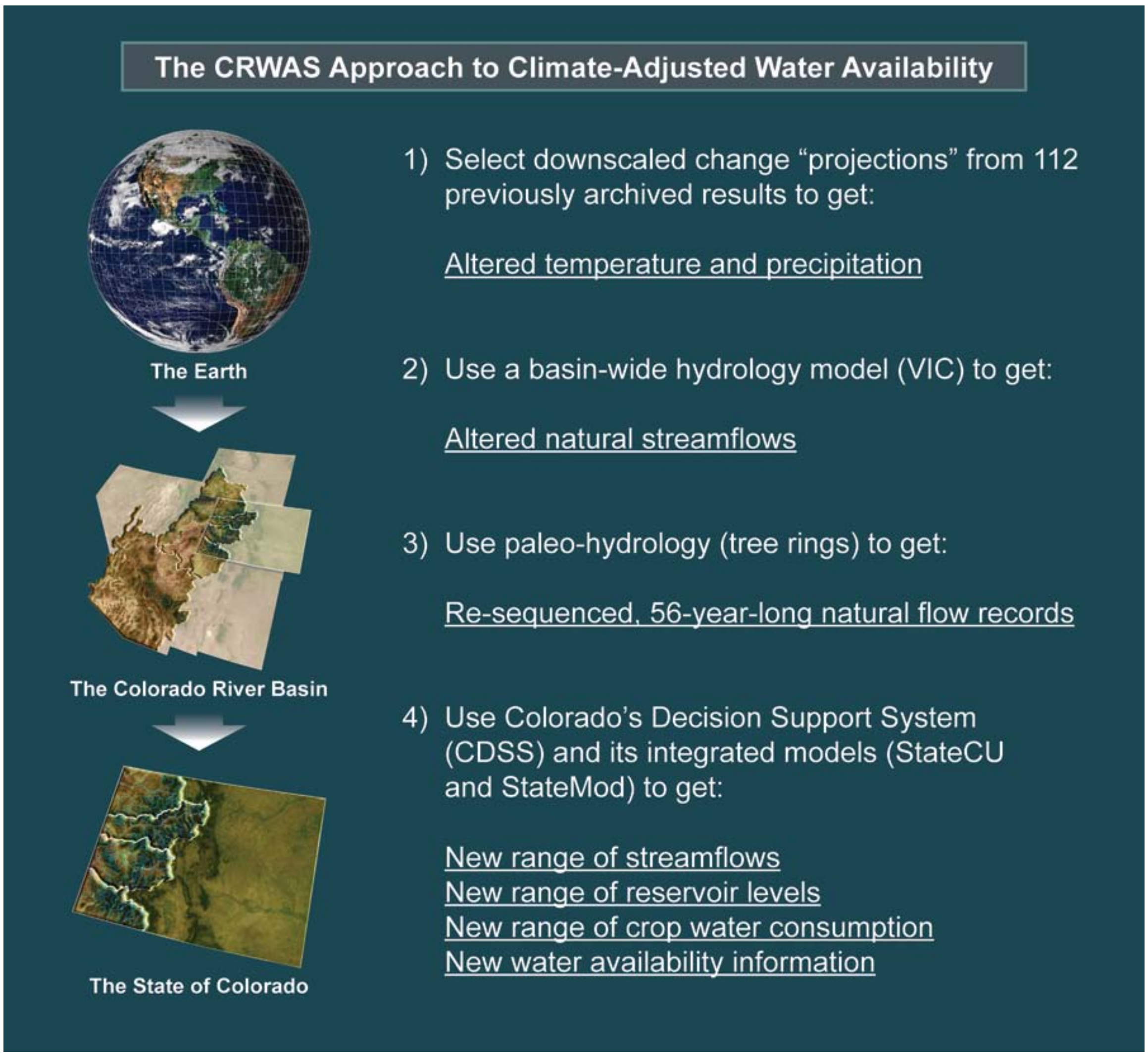
2. **Extended Historical Hydrology** – Also referred to as "paleo-hydrology", this approach extends historical records using information from more than 1,200 years of previously published tree-ring records. The lengths of the wet and dry periods have significant effects on water availability for future use. Phase I of the CRWAS reviews alternative methods for correlating annual tree growth with streamflow and concludes that a "re-sequencing" approach best serves the needs of the Study. This approach focuses on the probabilities of transitioning back and forth between wet and dry years. It does not use the tree-ring data to increase or decrease the magnitudes of the maximum and minimum natural flows in the historical records, it simply rearranges the years, resulting in longer wet and dry periods.

3. **Climate-Adjusted Hydrology** – This approach assesses the magnitude of future water supply availability considering the effects of projected changes to climate. This Study reviews many methods to incorporate information from the climate projections that are available for the Colorado River basin. After coordinating with the State's CCTAG and the Joint Front Range Climate Change Vulnerability Study (JFRCCVS), the CRWAS uses five projections for each of the 2040 and 2070 planning horizons (ten total). A hydrology model is used to translate projected changes in temperature and precipitation to changes in natural flows throughout the river basin. Colorado's consumptive use model, StateCU, is used to estimate altered crop water needs resulting from higher temperatures and longer growing seasons. Figure ES-4 provides an overview of the process used to estimate the possible effects of climate change.

Table ES-1 summarizes the technical approach for all aspects of the CRWAS Phase I work including the effects of climate-adjusted hydrology.

Approach to Evaluating the Effects of Climate Change

Approach: The CRWAS approach to evaluate the effects of potential climate change on our State's water availability begins by using previously developed climate change projections. A hydrology model is then used to estimate effects on streamflow. The process includes consideration of extended historical hydrology and concludes with applying the State's sophisticated water planning models to simulate the response of our existing water rights and water supply systems to meet our water demands.



Result: Interested parties can use results to consider both historical hydrologic conditions and the potential effects of climate change in planning their future capital expenditures and risk management strategies.

Figure ES-4 – Adjusting Historical Hydrology to Consider Potential Climate Change

Table ES-1 – Phase I Technical Approach Summary

Historical Hydrology	**Data and Tools:** CDSS (StateCU and CDSS Natural Flows) **Results:** Historical Natural Flows, Modeled Streamflows, Consumptive Use, Reservoir Levels and Water Availability **Includes natural flow hydrology observed for period 1950–2005**
Extended Historical Hydrology	**Data and Tools:** Extending Paleo Datasets **Results:** Extended Natural Flows, and Wet/Dry Spell Statistics **Extended record dating from AD 762 (more than 1,200 years)** • Provides estimated natural flow traces. Flow magnitudes taken from historic flow record (1950-2005). • Flow sequences developed using statistical models applied to tree-ring data. • Provides a wider variety of year-to-year flow sequences than historical record. • Re-sequencing – Future sequences of wet and dry years cannot be predicted; therefore, 100 different 56-year hydrologic traces were developed. All are considered equally probable.
Climate-Adjusted Hydrology	**Data and Tools:** Variable Infiltration Capacity (VIC) Model **Results:** Climate-Adjusted Temperature, Precipitation, and Natural Flows **Based on the selection of five climate projections for each of the 2040 and 2070 planning horizons** • Used same five 2040 projections selected in the JFRCCVS; however, obtaining five appropriately distributed projections for CRWAS study conditions required different projections for 2070. • Each of the selected downscaled climate projections is treated as equally probable. • Temperature and precipitation changes were translated into effects on natural flow using the VIC hydrologic model. Flow sequences (dry/wet spells) were derived from those seen in the paleohydrology flow record.

Table ES-1 – Phase I Technical Approach Summary (cont.)

Climate-Adjusted Irrigation Demands	**Data and Tools:** CDSS (StateCU) **Results:** Climate-Adjusted Irrigation Demands **Superimposes historical or projected mean monthly temperature and total monthly precipitation on current irrigated acreage and crop types to estimate crop irrigation requirements (CIR).** • StateCU uses temperature-based monthly Blaney-Criddle approach, incorporating available locally calibrated coefficients to determine CIR. • Temperature triggers allow growing season start and end dates to reflect changes under varying climate conditions.
Water Allocation Modeling	**Data and Tools:** CDSS (StateMod) **Results:** Climate-Adjusted Streamflow, Water Availability, Reservoir Operations, and Consumptive Use **Reflects historical or projected climate-based natural flows, crop demands, and irrigation head gate demands.** • Uses current M&I demands, transmountain exports, reservoir capacities, and basin operations. • StateMod allocates historical or projected natural flows to meet demands based on Colorado water rights, current administrative agreements, and current reservoir operations. • Model provides physical streamflow and water available for future demands at 2,000+ locations throughout the Study Area. Includes reservoir use, diversions, and consumptive use.

Technical Findings

The detailed technical approaches presented in the preceding section were developed in a transparent manner considering the input and direction of CWCB staff and Directors, IBCC and BRT members, the State's CCTAG and many representatives of many non-governmental organizations and stakeholders. A major finding for the CRWAS is that the methodology adopted, that built on existing data; existing models; and existing procedures, is a valid technical approach uniquely suited for the study. The use of readily-available down-scaled climate projection information, the robust VIC hydrology model, and the CDSS processes, models, and data sets provide a comprehensive way to assess water availability and operational effects for historic, extended historic and climate-adjusted hydrologies.

CRWAS findings are presented for the three alternative hydrologic cases: historical hydrology from the 1950 through 2005 study period, alternate historical hydrology incorporating information from tree-rings to allow an extended view of variability, and alternate hydrology associated with potential future climate conditions. Average monthly hydrograph charts and low flow comparison charts are presented in the report and appendices. In addition, these findings can also be accessed, viewed, and downloaded through the CRWAS Data Viewer (http://cwcb.state.co.us) where time series flow charts can be tailored to a user's specific interests. This accessibility of results for each hydrology scenario analyzed at locations throughout the basin specifically addresses the feedback received during the CRWAS public outreach efforts. The information is available for water users and providers to: (1) access model results at specific locations of interest; (2) perform statistical analyses based on selected hydrology and locations and (3) make decisions on which hydrologic datasets to use for planning purposes.

Study results for historic hydrology are provided in combination with climate-adjusted hydrology in the main report and in the appendices, for the following parameters:

- Temperature
- Precipitation
- CIR
- Natural Flow
- Modeled Streamflow
- Water Available to Meet Future Demands
- Modeled Reservoir Storage
- Modeled Consumptive Use

The ensemble of 100 56-year-long natural flow traces that constitute the extended historical hydrology is characterized by statistical analyses that allow comparison to the historical record.

Table ES-2 summarizes general technical findings of CRWAS Phase I, comparing conditions for the 2040 and 2070 climate projections with historical conditions.

Table ES-2 – Primary Phase I Findings Based on 2040 and 2070 Climate Projections

Temperature

- Increase is less than the Study Area average increase at northern climate stations (e.g., Grand Lake, Yampa, and Hayden)
- Every climate projection shows an increase in average annual and monthly temperature
- 2070 temperatures are higher than 2040

2040	Study Area average annual increases range from 1.8 °F to 5.2 °F
2070	• Study Area average annual increases range from 4.8 °F to 8.1 °F

Precipitation

- Generally increases in the winter months and decreases in the summer months
- Average winter increases are larger in the northern portion of the Study Area, and smaller in the southwestern portion of the Study Area
- Increase in temperatures causes a shift from snow to rain in the early and late winter months

2040	• Study Area winter average changes by 102% to 116% of historical • Study Area April through October average changes by 82% to 105% of historical
2070	• Study area winter average changes by 99% to 127% of historical • Study Area April through October average changes by 93% to 99% of historical

CIR

- Increases for each of the climate projections throughout the Study Area
- Increases are primarily due to higher temperature and lower irrigation-season precipitation, which increase:
    - the number of days in the growing season for perennial crops, and
    - the crop demand for irrigation water
- Peak continues to occur in the same month as it has historically

2040	• Study Area average annual CIR increases by 1.9 to 7.4 inches for individual climate scenarios. • Study Area average annual growing season increases by 8 to 32 days
2070	• Study Area average annual CIR increases by 5.1 to 10.9 inches for individual climate scenarios. • Study Area average annual growing season increases by 21 to 46 days

CIR for Study Basins

- Every Study Basin shows an increase for all climate scenarios
- The White River basin shows the largest percentage increase
- The Yampa River basin shows the smallest percentage increase

Table ES-2 – Primary Phase I Findings Based on 2040 and 2070 Climate Projections (cont.)

Natural Flow

Historical Hydrology

- The longest (historic) wet spells range from 4 to 16 years in length, with only 4% longer than 7 years
- Historic dry spells range from 3 to 11 years in length with 95% being 5 or 6 years long
- Moving from north to south, historic dry spells generally become shorter and historic wet spells generally become longer

Extended Historical Hydrology

- The return interval of historic wet and dry spells vary widely from location to location
- Return intervals are shorter for locations that have shorter historic spells and longer for locations that have longer historic spells.
- At 90% of the sites, the return interval of the historic dry spell ranges from about 8 to about 200 years, and the return interval of the historic wet spell ranges from about 13 to about 100 years
- In very general terms, locations with shorter historic spells should expect longer spells and vice versa

Climate-Adjusted Hydrology

- At over 80% of the sites, the majority of climate cases suggest a decrease in annual flow for both 2040 and 2070
- Annual flow is more likely to increase in parts of the Yampa River basin and in some higher elevation watersheds
- Annual flow is more likely to decrease in southwestern watersheds and at lower elevations
- At 75% of locations, all climate cases showed a shift toward earlier runoff, and at all locations, some climate cases showed a shift toward earlier runoff
- Higher peak flows may be beneficial for riparian health; however, lower flows in late summer and fall may impact other non-consumptive needs

2040	• At three locations, all climate cases showed increases in average annual flows. At the remaining 224 locations, the climate cases contained the historic average annual flow • Runoff shifts earlier by an average of 8 days
2070	• At 17 locations, all climate cases showed increases in average annual flows. At 74 locations, all climate cases showed a decrease in average annual flows. At the remaining 136 locations the climate cases contained the historic average annual flow • Runoff shifts earlier by an average of 14 days

Table ES-2 – Primary Phase I Findings Based on 2040 and 2070 Climate Projections (cont.)

Modeled Streamflow	
2040	• Flows are generally higher than historical in May and June and lower in July through March • Flows are generally lower than historical in three of the five climate projections, but generally higher than historical in two projections • The historical annual low-flow values generally fall within the range of projected low-flow values
2070	• Some 2070 projections show greater average annual modeled streamflow compared to 2040 projections • Locations in the northern portion of the Study Area and higher elevation locations in the upper Colorado basin generally show increases in average annual modeled streamflow • The historical annual low-flow values generally fall within the range of projected low-flow values in the Yampa, White, and Colorado basins. However, the range of projected low-flow values is generally lower than historical low-flow values for locations in the Gunnison basin and in the southwestern portion of the Study Area • The historical annual low-flow values in the northern portion of the Study Area generally show a wider range between the five individual 2070 climate projections than between the five individual 2040 climate projections • The historical annual low-flow values in the central and southern portions of the Study Area generally show a narrower range between the five individual 2070 climate projections than between the five individual 2040 climate projections
Water Available to Meet Future Demands	
• Upstream locations on main rivers and smaller tributaries generally have less flow available to meet future demands as a percent of modeled streamflow than gages farther downstream that include more tributary inflow	
2040	• Most locations show less water availability for three of the five climate projections. However, for one of the projections, the locations selected to display CRWAS results show more water available • The climate projections generally indicate more water availability in April and May, corresponding to the shift in the natural flow hydrographs • The historical annual minimum water availability values generally fall within the range of projected minimum water availability values for 2040 throughout the Study Area
2070	• Most locations in the Study Area show less water availability for four of the five climate projections. The exception is the southwestern portion of the Study Area, which generally shows less water availability for all five projections • The range of projected annual minimum water availability values is generally larger in 2070 compared to 2040 in the northern portion of the Study Area, but smaller in the central and southern portions of the Study Area • The historical annual minimum water availability values generally fall within the range of projected minimum water availability values for 2070 in the northern and central portion of the Study Area

Table ES-2 – Primary Phase I Findings Based on 2040 and 2070 Climate Projections (cont.)

Modeled Reservoir Storage

- Earlier peak runoff, reduced flows during the peak irrigation season, and increased crop demands result in more use of reservoirs (more reservoir fluctuation)

2040	• Reservoirs are generally drawn down to lower levels, and generally fill to historical levels
2070	• Reservoirs are generally drawn down to lower levels, and do not fill to historical levels, except in the northern portion of the Study Area

Modeled Consumptive Use

- Average annual consumptive use in the Yampa, White, Upper Colorado, and Gunnison basins is greater for every climate projection. Average annual consumptive use in the San Juan basin is less for every climate projection
- Total consumptive use for the Study Area is greater than for historical climate conditions for most climate projections
- Although modeled consumptive use generally increases, not all crop demands are met in any basin. Similar to historical conditions, there continue to be water shortages on tributaries and in the late irrigation season for the projected conditions

2040	• Projected consumptive use increases in most months in every basin except the San Juan. Projected consumptive use in the San Juan generally increases in spring months only
2070	• Projected consumptive use increases in April, May, and June for every basin, with the exception of the San Juan basin. Projected consumptive use is higher in every month in the White River basin • Projected consumptive use for the 2070 projections is higher than for the 2040 projections in every basin except the San Juan.

Conclusions and Recommendations

Phase I of the CRWAS responds to the General Assembly's direction to the CWCB to provide information on how much additional water is available from the Colorado River basin to meet the State's future consumptive and non-consumptive water needs. In accordance with IBCC input in the scoping process, Phase I presents water availability based on current levels of water use, existing water supply systems, and current interpretations of operating and management practices.

An important aspect of the Phase I work is that it is transparent and accessible. Analysis methods and refinements to modeling tools were reviewed extensively with BRT representatives, including the owners and operators of the major water supply systems. Results are presented for three alternative hydrologic cases, including those based solely on historical hydrology. This process allows individuals and agencies to consider a broad range of potential future hydrologic conditions in their water management decisions.

Because of that transparency, the tools, and the detailed database of natural flows, water use and modeled conditions provided by Phase I will serve as a foundation for future Study phases and other analyses, by the State and others. Subsequent CRWAS phases would likely consider potential new water supply projects, additional non-consumptive water demands and revised water management strategies intended to meet those demands to the greatest degree with consideration for acceptable risk.

Important conclusions and recommendations of the Phase I Study are summarized in four general categories: Technical; Study Processes and Supporting Accomplishments; Utilization of Phase I Results, and Future Analyses.

Technical Results

The technical approach and findings presented in the previous sections document the geographic breadth and engineering sophistication of the CRWAS. The datasets and modeling tools of the State's CDSS proved to be well-suited for addressing current water management operations and the effects of potential future hydrologic conditions. Extensive streamflow, reservoir storage, consumptive use and other important data are now available throughout the Study Area for current water management operations superimposed on historical hydrology, extended historical hydrology and climate-adjusted hydrology.

1. **Historical Hydrology -** The analysis of Historical Hydrology results in new water resource data throughout the Study Area based on the latest adjustments to the CDSS models. Historical hydrology has long been used in estimating the reliable yields of Colorado water supply systems. The magnitude and duration of droughts in relation to the wet periods that refill reservoirs are critical in analyzing our ability to meet current and future consumptive and non-consumptive water needs. The longest wet spells in the 56-year record (referred to as the "historic spell") range from 4 to 16 years in length across the 227 locations in the Study Area where natural flows are determined, with only 4 percent of historic wet spells longer than 7 years. Historic dry spells range from 3 to 11 years in length with 95 percent of dry spells being 5 or 6 years long. Moving from north to south, historic dry spells generally become shorter and historic wet spells generally become longer.

2. **Extended Historical Hydrology -** The Extended Historical Hydrology showed that the length, intensity and frequency of wet and dry spells vary significantly across the Study Area. The expected frequency with which a dry or wet spell of length equal to the historic spell will return also varies considerably from location to location, so conclusions about the expected recurrence of spells must be made on a site-specific basis. In general, the Extended Historical Hydrology shows that significantly longer dry periods occurred prior to recorded history.

3. **Climate-Adjusted Hydrology -** For the Climate-Adjusted Hydrology, some projections of future conditions show increased flows at the majority of locations compared to historical conditions; however, most projections show reduced flows. Projected flows generally show a shift toward earlier runoff. At most locations and for most projections, future conditions show an increase in precipitation in the winter and a decrease in precipitation during the summer. All projections show an increase in temperature. Decreased precipitation and increased temperature during the growing season lead to increased crop irrigation requirement. This, combined with a tendency for runoff to occur earlier, contributes to increased fluctuation in reservoir contents and, generally, lower end-of-year contents. The projections also indicate that the southern part of the State may be generally drier (less Natural Streamflow, Modeled Streamflow, and Water Available to Meet Future Demands) than northern parts of the State.

Readers are encouraged also to review the details presented in Table ES-2, the main report and its appendices as well as the on-line CRWAS Data Viewer to gain a more complete understanding of water availability in the Study Area.

Study Processes and Supporting Accomplishments

1. **IBCC and BRT Involvement** – Interaction with the IBCC and the BRTs provided essential context for the work performed, especially concerns regarding the Study's methods and outcomes. The interaction helped mold the Study and ensure that the results of the initial CRWAS process provide a strong foundation for future work. The interaction and educational workshops also facilitated improvements, and enhanced trust in the State's CDSS planning tools.

2. **Public Outreach** –General public input also shaped the Phase I study. Numerous meetings, including but extending well beyond the official IBCC and BRT meetings, provided important forums for sharing the complex issues and tools of the CRWAS. Formal comments provided by more than 30 entities on the Draft CRWAS Phase I Report helped improve the Study and its results. These comments were carefully considered by the CRWAS Team and, in response, the CWCB authorized extensive additional outreach workshops and the preparation of a 115-page response matrix. The response matrix provides the State and its water stakeholders with valuable documentation about water management concerns and supports statewide communication and collaboration in water planning. As the Study transitions into additional phases, a similar level of outreach may be an important part of intrastate dialogue to guide water supply and demand analyses for a variety of potential planning scenarios. Public outreach should continue to include education and review of CDSS models; ongoing refinements are recommended to advance the value of the State's analysis tools.

3. **Access to Data and Modeling Results** – Water availability is highly dependent on the characteristics of a particular use—the priority and magnitude of its water rights, the physical supply available at its location and the capacity of its facilities. No single report can provide enough detail to address the thousands of Colorado water uses within the Colorado River Basin. Through the CRWAS public outreach activities, it became clear that stakeholders required simplified access to all of the detail of the CRWAS data and modeling results in order to use the Study results effectively. An online CRWAS Data Viewer now provides a means to quickly and easily:

    - Explore over 2,000 CRWAS model locations on interactive maps.
    - View and compare streamflows, reservoir contents, diversions and other data for the 5,500 final CRWAS model runs representing historical, alternate historical, and climate projected conditions.
    - Download CRWAS model data in user-friendly spreadsheet format for stakeholders to prepare additional analyses and tailor their own presentations.

    The CRWAS Data Viewer allows anyone with internet connection to easily access hundreds of gigabytes of CRWAS information without having to download and learn new and complex software. This application will help stakeholders consider their own assessments of future opportunities and risks. The CRWAS Data Viewer and corresponding User Manual are available through an internet link on the CWCB website. During CRWAS public outreach workshops, CWCB received positive feedback on the usefulness of the CRWAS Data Viewer. This application should be updated, as necessary, to respond to initial public use and to allow continued public use through subsequent phases of the CRWAS and other state programs.

Utilization of Phase I Results

1. **Support for other State Programs** – As listed on Figure ES-2, the many ongoing State-sponsored programs and processes are interconnected with each other and with the CRWAS. Hydrologic data and modeling tools from CRWAS Phase I and subsequent phases will support many other State programs and processes. CRWAS can also support several of Governor Hickenlooper’s goals for the IBCC and BRTs in further implementation of the Water for the 21st Century Road Map including:

    - Increase education, specificity, support, engagement, and regional cooperation in the IBCC framework.
    - Support common understanding of statewide water problems and solutions.
    - Support interchange of ideas between State, water providers, and project proponents.
    - Support BRT portfolio development and assist in identifying methods to meet regional needs.

2. **Availability of Results for Historical Hydrology** – Traditionally, water supply agencies have relied extensively on historical information on water supply as an indication of likely future conditions, the premise being that history tends to repeat itself. Because the CRWAS also includes analyses for paleohydrology and climate change hydrology, much of the focus in public outreach meetings and in presenting Phase I results necessarily focused on aspects of these less-familiar topics. The data and modeling results for today’s level of demands superimposed on historical natural flows are presented in Phase I of the CRWAS and available through the CRWAS Data Viewer.

This information provides the foundation on which stakeholders' can assess their future water management strategies.

3. **<u>Perspectives on Climate Change Projections</u>** – Phase I of the CRWAS compares the effects of three alternative water supply cases (historic hydrology, extended historical hydrology, and climate-adjustedhydrology). Phase I results and models allow Colorado River water managers, policy makers, and stakeholders to consider wide ranging hydrologic scenarios and base their water management decisions on their own risk management strategies. With the CRWAS information, they can base their planning decisions on their own level of confidence in the historic hydrology, paleohydrology, or climate-adjusted hydrology.
4. **<u>Perspectives on Uncertainty</u>** –The CRWAS addressed the uncertainty in projections of future climate conditions by selecting five climate "cases" for each future time frame. The projections were selected to cover approximately 80 percent of the range of conditions projected by the 112 readily available climate model runs. The results of the CRWAS analyses, which are based in part on the selected projections, reflect the uncertainties in climate modeling. The range of results is large—in some cases and locations the selected climate projections lead to higher streamflows and in some cases they lead to lower streamflows; and this is a realistic reflection of the state of climate science at this time.
5. **<u>Foundation for Water Resource Planning –</u>** Phase I is not prescriptive, with no grand conclusions suggesting that water managers take specific actions. Instead, Phase I provides a tremendous amount of data about a variety of possible future hydrologic conditions, allowing study users the freedom to interpret the data in context with their own programs, priorities and water management systems. Based on comments received on the previous draft report, many water agencies may focus on historic hydrology in the planning and financing of major capital investments but may also consider, in a more qualitative fashion, the impact of potential climate change on these decisions. This approach anchors the policy-making process in the context of the historical hydrology while still considering vulnerabilities that may be faced if the future hydrologic conditions prove to be significantly different than they have been in the past.

Future Analyses

1. **<u>Stakeholder Interest in Assessment of Water Availability under Future Demands –</u>** Phase I results are based only on current water uses (current irrigated acreage, M&I demands, and non-consumptive water demands). In the Study presentations and workshops, and in written comments submitted on the previous draft report, many stakeholders expressed interest in the analysis of water availability considering future levels of consumptive and non-consumptive water demands, and analysis of potential water supply solutions including new water supply projects, new non-consumptive use programs and protections, and new water management strategies - all supporting a more robust assessment of risk management strategies.

2. **<u>Alternative Transbasin Water Demands affected by Climate Change</u>** – Climate change in eastern Colorado may affect demands for Colorado River water. In Phase I of the CRWAS, transbasin demands were not adjusted to reflect the effects that climate change may have on current levels of demand in the South Platte River and Arkansas River basins. As the State continues its programs to develop Decision Support Systems for the South Platte and Arkansas River basins, the methods adopted in the CRWAS

may be appropriate to estimate projected climate-adjusted water availability for these adjacent river basins.

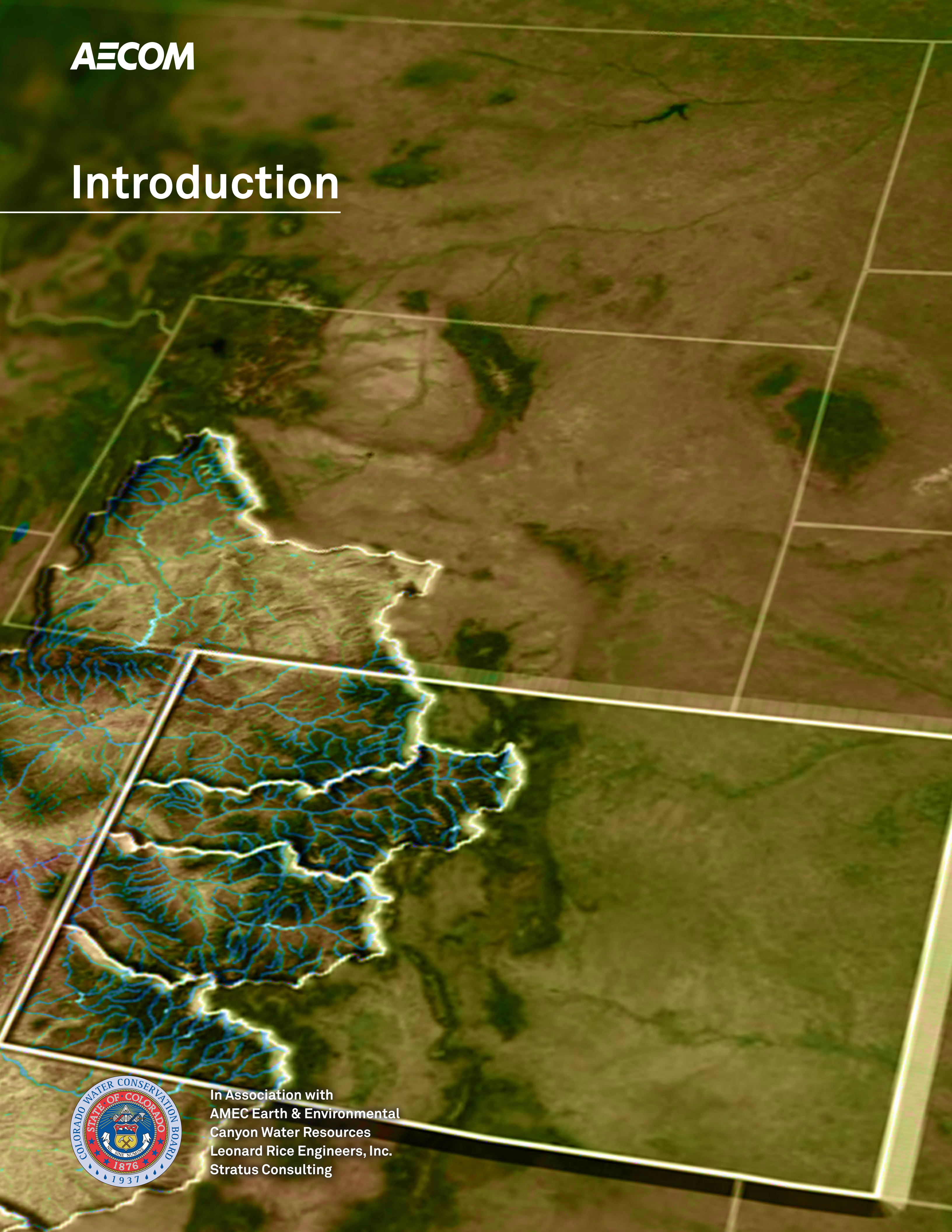
3. **<u>Consider Alternative Water Management Strategies and Interpretations of Existing Operational Agreements</u>** – Phase I results indicated that, under hydrologic conditions not experienced in the historic period, existing operational agreements, management plans, and annual reservoir operation plans may need to be interpreted in the context of these potential changed conditions. Subsequent phases of the CRWAS will provide opportunities to assess the effects of a broad range of reasonable interpretations and consider alternate operational strategies, including formal and informal agreements, affecting water management in the Study Area.

4. **<u>Collaboration with Other Studies and Incorporation of Independent Reviews of Methods and Results</u>** – Phase I demonstrated the benefits of independent input received from the IBCC, the BRTs, and other stakeholders and groups. Colorado is in an enviable position in terms of its resident professional expertise in water resource planning and management, its existing CDSS modeling tools, and the extensive climate change expertise in the state. Future CRWAS phases should continue to build upon the multiple CWCB / IBCC programs. Use of the CCTAG as a cost-effective and independent technical reviewer should continue, which will enhance the credibility of the State's programs like the CRWAS.

Final Thoughts for Colorado River Stakeholders

Phase I of the CRWAS provides Colorado River stakeholders with updated computer models and important new information on historic and future water availability. The CRWAS provides twelve different water supply scenarios based on historical hydrology, paleohydrology, and the ten climate change projections. The broad range of projected conditions poses a daunting challenge to planning. There is no single way to move forward with planning for water supply under profound uncertainty, but researchers and water resources managers are already developing planning approaches that begin to address the new types of uncertainty about long-term conditions. Scientists have been able to provide only very general (and sometimes contradictory) guidance about how to interpret projections of future conditions, but water managers have begun to consider practical ways to address uncertainty, and some useful resources are referenced in the body of this report.

Phase I results can be used by stakeholders to consider a broad range of potential future hydrologic conditions, better understand uncertainty in water management decisions, and support the development of specific policies and programs. It is recommended that each stakeholder entity interpret Phase I work from its own perspective, considering its own assessment of the possible future conditions, its role in water management, the resources it has at hand with which to adapt to alternative potential futures, and its tolerance for risk.



AECOM

Introduction

In Association with
AMEC Earth & Environmental
Canyon Water Resources
Leonard Rice Engineers, Inc.
Stratus Consulting

1 INTRODUCTION

1.1 Study Authorization

Colorado faces increasing demands on its water supply for both traditional consumptive uses (such as agriculture, municipal, industrial, and commercial uses) and for non-consumptive uses (such as environmental and recreational needs). Population growth; recent drought; oil, gas, and mineral development; and potential climate change broaden our concerns about the adequacy of Colorado's water supplies. Responding to these concerns, the Colorado General Assembly authorized the CRWAS through Senate Bill (SB) 07-122 and House Bill (HB) 08-1346. These bills direct the CWCB to conduct the Study: (1) in collaboration with the Interbasin Compact Committee (IBCC) and the State's river BRTs, and (2) with consideration for current and potential future in-basin consumptive and non-consumptive needs. These two directives led to broad-based and transparent public input, expanding the discussion from traditional types of consumptive water use to encompass environmental, recreational, and aesthetic uses of water.

A Study Team led by AECOM and including AMEC Environment & Infrastructure, Canyon Water Resources, Leonard Rice Engineers, Inc., and Stratus Consulting began work in late 2008, leading to a first draft of this report in March 2010. Recognizing the importance and interest in the Study, the CWCB set a 4-month public comment period and conducted extensive additional public outreach and technical analysis to respond to the broad range of comments received. To date, more than 60 public presentations and workshops about the CRWAS have been held with various groups including the CWCB's Board of Directors, IBCC, BRTs, Colorado Water Congress, and many others. The input and direction received from broad-ranging interests refined the focus and approach of the Study. It now provides more relevant and responsive information to Colorado water users, managers, policy makers, and stakeholders about current and potential future hydrologic conditions in the Colorado River tributaries that sustain our State's critical economic sectors and natural ecosystems. The Study is a source of useful water management information, but it is not intended to prescribe policies. Each organization, agency, and individual can interpret the Study results from its own perspective, considering its own assessment of the possible future conditions, its role in water management, the resources it has to adapt to alternative potential future conditions, and its tolerance for risk.

1.2 Study Phasing

Working closely with the IBCC, the CWCB is conducting the Study in multiple phases. Phase I (the subject of this report) is an assessment of water availability based on existing levels of water use (see Figure 1-1). For Phase I, the analysis of water availability focuses on current levels of water demands served by water rights now in use ("perfected" or "absolute" water rights). Phase I also focuses on interpretations of current operating and management practices for water diversion, storage, and conveyance facilities. For example, in scenarios where potential changes in climate conditions could affect the magnitude of water demands served by current water rights and irrigation systems, Phase I allows for the diversion of water up to the decreed maximum in the current water right. The difference between the crop's needs under new climate conditions and water diverted under the Phase I simulations is reported as a shortage.

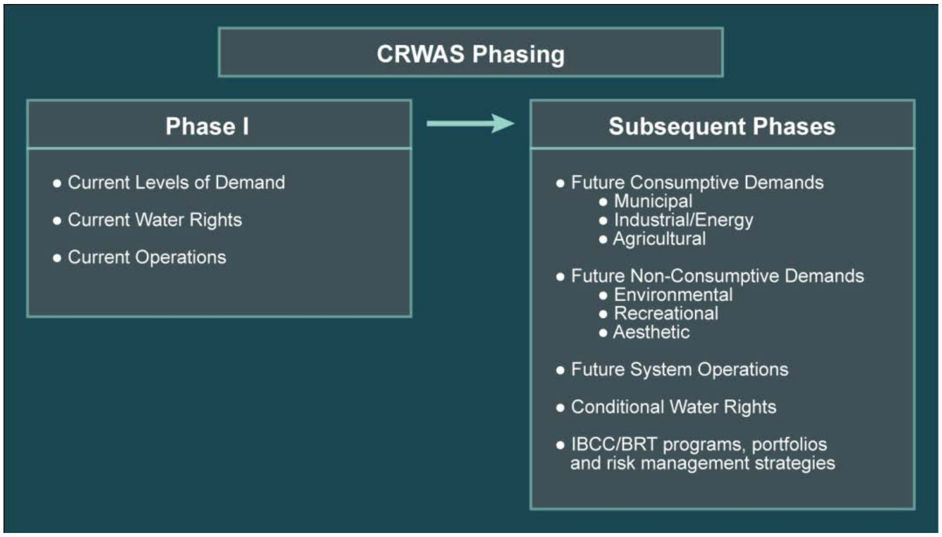


Figure 1-1 – CRWAS Phasing

The process of defining the potential future water demands , both consumptive and non-consumptive, that will be analyzed in subsequent phases of the CRWAS is currently underway through the State's IBCC processes coordinated by the CWCB. The primary focus of future phases will likely be to simulate the hydrologic effects of the various water demand scenarios, water supply portfolios, and potential changes to existing project operations. Subsequent phases will lay the foundation for individual or collective assessments of risk and potential strategies to manage or minimize risk. Regardless of the scope of future phases, the information, tools, and modeling results from Phase I will continue to support a broad range of CWCB programs and responsibilities, including continuing assessments of:

- Streamflows and reservoir storage to support water supply
- Flood protection and management
- Instream flow protection
- Water conservation
- Endangered species recovery
- Intra-state, interstate, and federal issues and programs

As shown in Figure 1-2, there are many ongoing programs and processes that the CWCB performs or directs in close collaboration with other State agencies and programs. In addition to other State, federal and local agencies, the CWCB is coordinating closely with the IBCC and BRTs in reviewing the Study's methods and results.

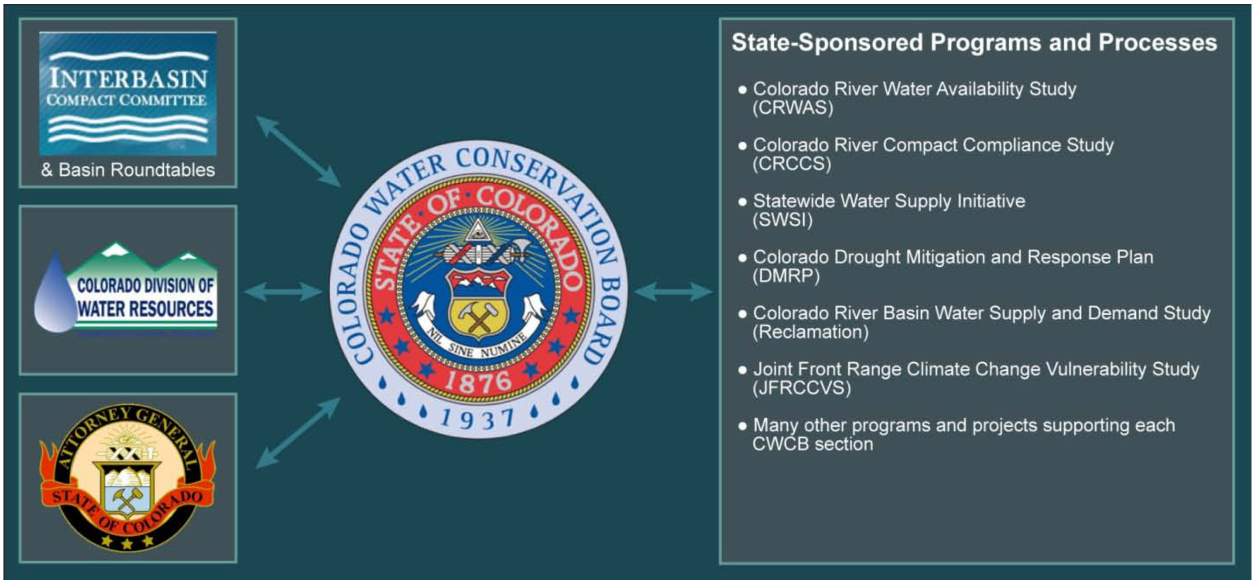


Figure 1-2 – State-Sponsored Water Management Programs Supported by the CRWAS

1.3 Study Area

The Study Area for the CRWAS encompasses the major tributary river basins of the Colorado River in the State of Colorado. Figure 1-3, presents the Study Area in accordance with the basins defined for the four West Slope BRTs. Elsewhere in this report, the basins comprising this Study Area are also referenced using the nomenclature of the Colorado Decision Support System (CDSS) for consistency in displaying modeling results. The CDSS consists of data and tools developed Statewide, plus models developed under basin-specific DSS efforts. The Colorado River DSS (CDSS) models were developed for the Yampa, White, Upper Colorado, Gunnison, and San Juan/Dolores basins. The term CDSS is used throughout this document to refer to both the larger CDSS effort, and the basin-specific development.

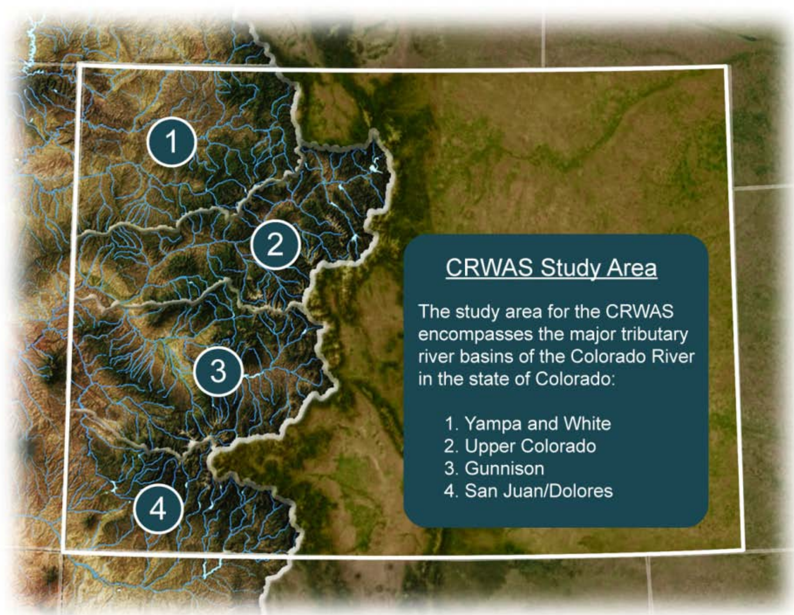


Figure 1-3 – CRWAS Study Area

1.4 Unique Attributes of the CRWAS

Studies considering the effects of climate change on water resources are being conducted world-wide; including two studies that have been completed, or are near completion, that cover a portion of the geographical area covered by the CRWAS. The Joint Front Range Climate Change Vulnerability Study (JFRCCVS), published in February 2012 by the Water Research Foundation, was undertaken to examine the potential effects that climate change may have on the supplies available to several Front Range municipal water agencies. The overlapping geographical area for the JFRCCVS and the CRWAS is the Colorado River main stem in Colorado and its tributaries. The U.S. Bureau of Reclamation is moving to finalize the Colorado River Basin Water Supply and Demand Study (CRBS) in the summer of 2012. This study completely encompasses the geographic area of the CRWAS and extends downstream to cover the entire Colorado River Basin. The primary purpose of the CRBS is to "define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin

States that receive Colorado River water over the next 50 years (through 2060), and to develop and evaluate adaptation and mitigation strategies to resolve those imbalances." Each of these studies inform stakeholders how water supplies may vary under changing climate conditions.

The JFRCCVS accomplished its goal of identifying changes to natural flow at 18 river locations for five climate projections representing 2040 and five representing 2070. As discussed in more detail in Section 2.3.4, the CRWAS investigated the same scenarios for 2040 but chose different projections for 2070 that better represented its study area. The JRCCVS scope did not include investigating how climate change may affect basin demands, nor did it investigate how climate change may affect future agricultural water consumption, affect water available to satisfy other specific water uses, or affect operations of existing water supply systems.

The CRBS identified changes to natural flow at 29 locations throughout the entire Colorado River basin reflecting estimated annual change through 2060, including locations in seven states, for all 112 available climate projections. They developed relationships based on degree increases in temperature and annual changes in precipitation to adjust their aggregated irrigation demands to reflect climate change. Finally, they used the Colorado River Simulation System (CRSS) model with the revised natural flows and demands to identify supply and demand imbalances in both the Upper Colorado and Lower Colorado river basins. Although the CRSS model does not include specific water rights or non-federal project operations in Colorado, it does represent the critical operations of Lake Powell and Lake Mead.

The State of Colorado has developed tools that allow the CRWAS to go well beyond both the JFRCCVS and the CRBS studies to investigate how climate change may affect water availability at the water user and water rights level, and how climate change may affect reservoir use and operations. The approach adopted by CRWAS may be the most detailed look at how specific water users may be impacted by climate change performed to-date anywhere in the world. This was made possible because of the availability of the CDSS model datasets previously developed for the Colorado River in Colorado. CDSS model datasets have not been fully developed for either the South Platte or the Arkansas River basins; therefore were not available for use in the JFRCCVS.

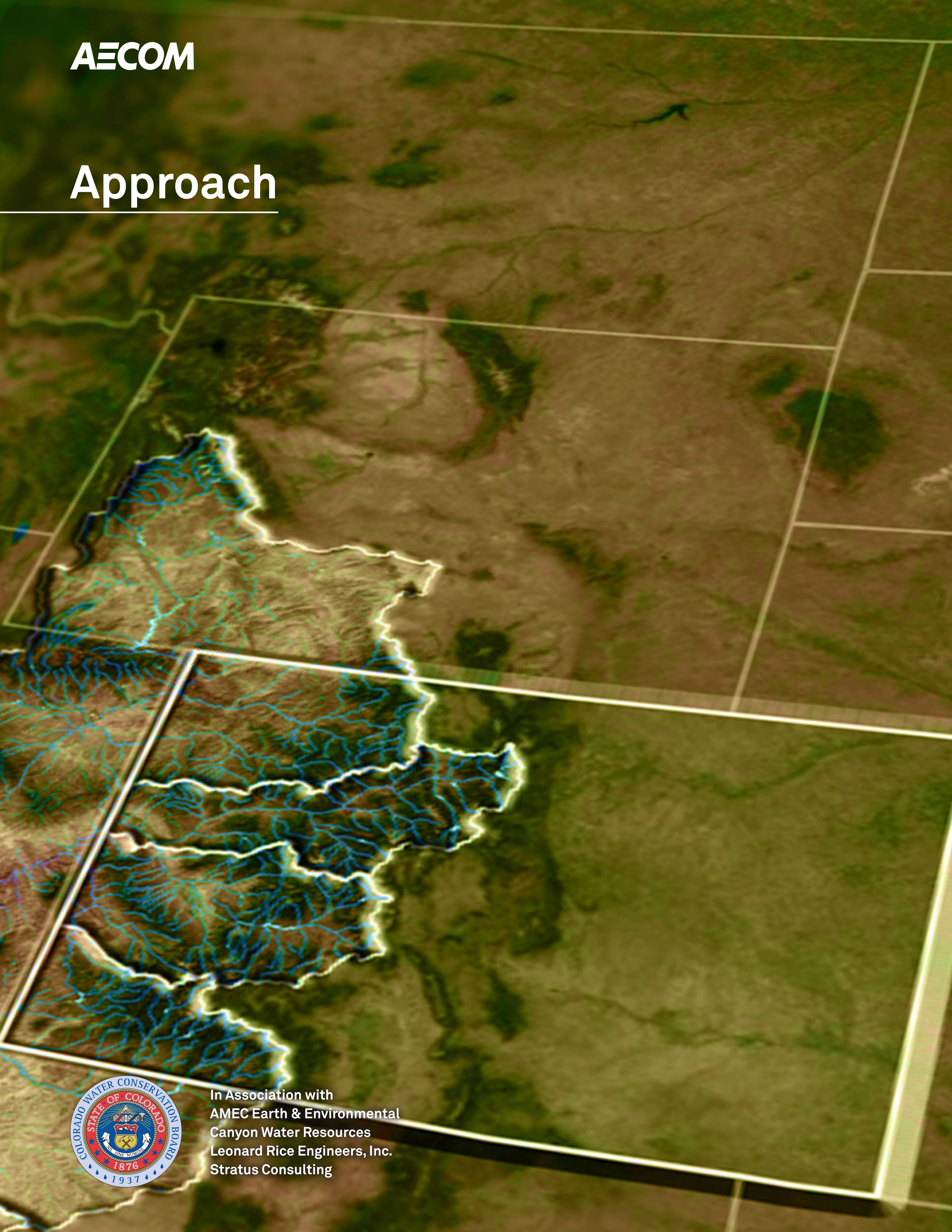
The existing CDSS consumptive use model (StateCU) datasets represent 100 percent of the current estimated irrigated acreage and irrigation practices at the ditch level. The existing CDSS water allocation model (StateMod) datasets represent the current water rights and administrative agreements, water user demands, and basin operations superimposed on natural flows throughout the Study Area. The availability of these datasets allowed the CRWAS to revise crop demands at the ditch level, using StateCU, to reflect current acreage and crop types and potential changes to growing seasons based on more locally estimated climate change parameters. Diversion demands, again at the ditch level, were adjusted to reflect crop demands. StateMod was then used to superimpose streamflows and climate-altered water use using Colorado's current water rights, administrative rules and agreements, and operational practices. The results provide detailed information on consumptive use; shortages; physical streamflow; and water available for future use at more than 2,000 locations throughout the Study Area. In addition, reservoir use (storage and releases) are provided for more than 60 federal and non-federal reservoirs throughout the Study Area.

Each of these three complementary studies help inform stakeholders how water supplies may vary under changing climate conditions. The JFRCCVS focuses on potential changes in natural flows that may affect Front Range municipal water providers and the CRBS focuses on potential changes in natural flows and federal reservoir operations throughout the seven-state Colorado

River basin. The CRWAS includes effects on natural flow but extends the analysis to consider resulting changes in crop consumptive use, federal and non-federal reservoir operations and remaining water availability for consumptive and non-consumptive purposes.

Key Colorado Water Supply Questions and the Studies and Processes to Provide Answers

- **What are Colorado's water needs?**
  - *Consumptive and Non-consumptive Water Needs Assessments* (IBCC and BRTs with CWCB facilitation)
- **What water is available under current and future conditions?**
  - *CRWAS Phase I* (CWCB with IBCC and BRTs)
  - *CRWAS Phase II* (CWCB with IBCC and BRTs)
  - *Colorado River Basin Supply and Demand Study* (Reclamation with support from Colorado River Water user organizations)
- **What could we do to meet these needs?**
  - *Strategies for Colorado's Water Supply Future* (CWCB with IBCC and BRTs)
  - *Basin Needs Decision Support System and IPPs* (CWCB with IBCC and BRTs)
  - Filter Through Vision Goals (CWCB with IBCC and BRTs)
- **How do we ensure that Colorado's future is the one we want?**
  - Use Portfolio Tool (CWCB with IBCC and BRTs)
  - Build Portfolios and Scenarios (CWCB with IBCC and BRTs)
  - Develop Framework (CWCB with IBCC and BRTs)
- **How are we going to mitigate the risks?**
  - *Colorado River Compact Compliance Study* (CWCB with DWR and AG's Office)
  - *State Drought Plan* (CWCB)



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COLORADO WATER CONSERVATION BOARD
STATE OF COLORADO
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2 APPROACH

2.1 Overview

Water availability studies like the CRWAS compare water supply and demand based on the "supply-and-demand equation":

Water Available for Future Uses = Supply – Demand

Supplies and demands vary from day to day. They vary seasonally and they vary in dry years and wet years. Complex computer models are used to track the water supplies in streams and reservoirs and to reflect the actions of water managers as they operate supply systems to minimize shortages and as they deal with increasing competition for water among cities, industry, agriculture, recreation, and the environment. The flexibility of water managers to minimize shortages is constrained by the terms of their water rights, operation plans and water exchange agreements.

A primary challenge in conducting a comprehensive water availability study is developing the tools (computer models) needed to: (1) mimic natural phenomena as water flows through drainage basins, and (2) simulate the operations of stream diversion structures and reservoirs, and (3) represent flows returning to streams from cities, farms, and industry - all operating under the umbrella of Colorado's Prior-Appropriation Doctrine. Fortunately for the CRWAS, the State of Colorado had the foresight to invest in the development of comprehensive computer tools over the past 15 years that allow this study to be performed with relative efficiency and in great detail. The CDSS, with its integrated databases and simulation models, is likely the most comprehensive, transparent, and geographically extensive system for water supply analyses available anywhere in the U.S.

The health of Colorado's forests is very important to regional ecological conditions that have potential effects on water supplies. Phase I of the CRWAS reviewed the practicality of modeling the hydrologic effects of recent and on-going changes in our forest lands as part of the Study's focus to assess long-term water supply availability.

The U.S. Forest Service (USFS), in conjunction with the CWCB and the North Platte River Basin Roundtable, is conducting a multi-year study to collect information regarding the forest change processes that most influence the hydrology of disturbed forests in Colorado. Given that the focus of Phase I of the CRWAS is to evaluate long-term water availability, it is appropriate to re-assess quantifying the impact of forest change on water availability when results of the USFS work are available and the science of forest change assessment is more advanced.

The March 2010 Draft CRWAS Phase I Report provided quantitative estimates of the amount of consumptive use, above existing levels, that can occur within Colorado under certain Colorado River Compact assumptions ("water available for future consumptive use"). After careful consideration, the Study Team and the CWCB agreed that the preliminary analyses of the March 2010 Draft Report would be replaced with a summary of the complexities, challenges, and uncertainties inherent in estimating the magnitude of water available for future consumptive uses in Colorado. This summary is presented in Section 2.2.6 of the main report.

Phase I of the CRWAS is composed of two primary analysis components: 1) CDSS Refinements and 2) Water Availability Assessments as follows.

2.1.1 *Continuing CDSS Refinements*

The CRWAS leveraged the State's investment in the Colorado Decision Support System (CDSS) modeling tools. Through extensive public outreach and direct collaboration with water suppliers and managers, the models were reviewed and refined to further enhance general confidence in the models' ability to simulate streamflows and project operations, and to provide important information for future assessments of non-consumptive water needs. The refinements were thoroughly documented to support subsequent CRWAS phases and other future State water resource modeling and planning initiatives. The CDSS proved fully capable of simulating current water uses (demands) and alternate hydrologic cases to provide a broad range of results including physical streamflow, consumptive use, and water available to meet future demands throughout the Study Area under Colorado's Prior Appropriation Doctrine.

2.1.2 *Water Availability Assessments*

Phase I considers and compares three different conditions for water supply:

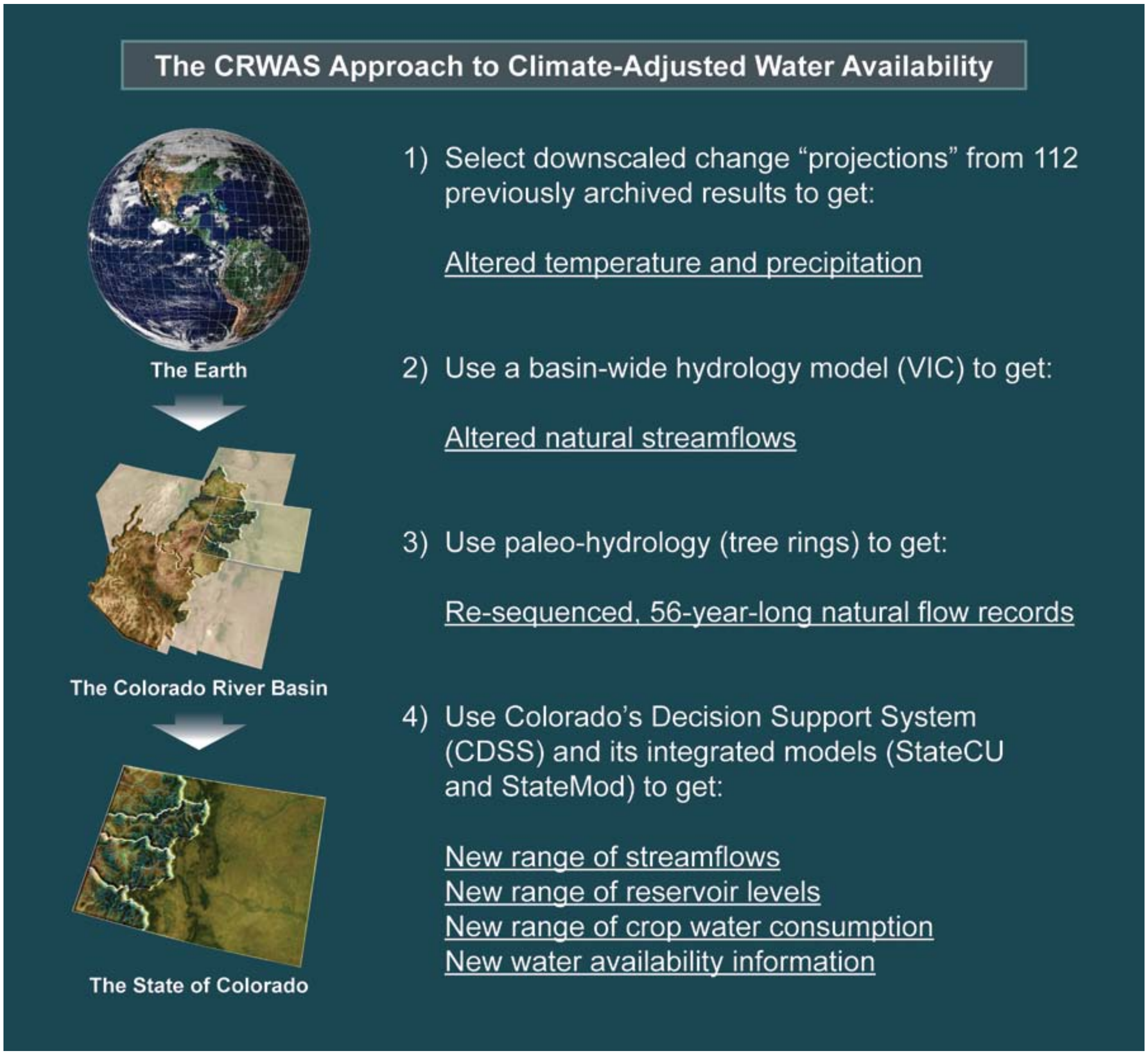
1. **Historical Hydrology** – Traditionally, water supply agencies have used recorded historical information on water supply as an indication of likely future conditions, the premise being that history tends to repeat itself. This Study uses a 56-year period to represent historical hydrology (1950 through 2005). This period includes both very wet and very dry years, contains the most reliable historical data upon which to base comparisons of the effects of climate change, and uses information that Colorado River stakeholders can relate to through their own experiences.

2. **Extended Historical Hydrology** – Also referred to as "paleo-hydrology", this approach extends historical records using information from more than 1,200 years of previously published tree-ring records. The lengths of the wet and dry periods have significant effects on water availability for future use. Phase I of the CRWAS reviews alternative methods for correlating annual tree growth with streamflow and concludes that a "re-sequencing" approach best serves the needs of the Study. This approach focuses on the probabilities of transitioning back and forth between wet and dry years. It does not use the tree-ring data to increase or decrease the magnitudes of the maximum and minimum natural flows in the historical records, it simply rearranges the years, resulting in longer wet and dry periods.

3. **Climate-Adjusted Hydrology** – This approach assesses the magnitude of future water supply availability considering the effects of projected changes to climate. This Study reviews many methods to incorporate information from the climate projections that are available for the Colorado River basin. After coordinating with the State's CCTAG and the Joint Front Range Climate Change Vulnerability Study (JFRCCVS), the CRWAS uses five projections for each of the 2040 and 2070 planning horizons (ten total). A hydrology model is used to translate projected changes in temperature and precipitation to changes in natural flows throughout the river basin. Colorado's consumptive use model, StateCU, is used to estimate altered crop water needs resulting from higher temperatures and longer growing seasons. Figure 2-1 provides an overview of the process used to estimate the possible effects of climate change.

Approach to Evaluating the Effects of Climate Change

Approach: The CRWAS approach to evaluate the effects of potential climate change on our State's water availability begins by using previously developed climate change projections. A hydrology model is then used to estimate effects on streamflow. The process includes consideration extended historical hydrology and concludes with applying the State's sophisticated water of planning models to simulate the response of our existing water rights and water supply systems to meet our water demands.



Result: Interested parties can use results to consider both historical hydrologic conditions and the potential effects of climate change in planning their future capital expenditures and risk management strategies.

Figure 2-1 – Adjusting Historical Hydrology to Consider Potential Climate Change

2.2 Scope Refinement and Supporting Activities

The contractual scope for Phase I of the CRWAS defined the overall approach for the Study including procedures and methods to be used. This scope anticipated that detailed approaches for certain tasks would need to be defined based on the results of previous work in the Study and on input received from others including external technical reviewers such as the CCTAG and diverse stakeholders comprising the IBCC and BRTs. The subsections that follow describe three key activities in this process: literature review, public outreach and coordination with other State-sponsored programs. These sections are followed by four key areas that were addressed through this process: refinements to the State water planning models; assessments of the impacts of on-going changes in forests in Colorado; effects of the Colorado River and Upper Colorado River Compacts; and treatment of uncertainty in water supply planning.

2.2.1 Literature Review

CRWAS activities included a significant level of literature review associated with Study activities. This included tasks to identify, review, and summarize relevant and readily available previous studies and investigations pertinent to the execution of primary Study tasks. Information on specific references is provided in CRWAS technical memoranda. See also the Reference section in this report.

Where to find more detailed information:

A concise list of documents most pertinent to CRWAS and summaries of those documents are provided in CRWAS Task 2.1 – *Pertinent Document List* and CRWAS Task 2.2 – *Summary Briefs*; comprehensive reference lists and literature reviews are provided in technical memoranda and modeling briefs associated with CRWAS Tasks; available at http://cwcb.state.co.us/.

2.2.2 Public Outreach

CRWAS activities included a significant level of outreach activities to communicate and share Study objectives, approaches, progress, and findings; to collaborate and participate with other organizations, programs, and processes focused on similar study objectives; and to solicit feedback on Study methods and techniques for presenting results. Outreach activities included newsletters; regular meetings with DNR, CWCB, DWR, and AG staff; and approximately 60 public meetings, presentations, and workshops with water users, managers, stakeholders, and other interested parties. This effort, enhanced statewide dialogue and fostering understanding of the CRWAS process through knowledge transfer to, and solicitation of feedback from, interested parties.

Outreach activities were able to take advantage of, and integrate productively with, the public communication efforts of the CWCB Water Supply Planning Section and on-going State-sponsored IBCC processes. Outreach activities also provided opportunities for interested parties to actively participate in development of State water resources modeling tools (e.g., CDSS), providing the State with an opportunity to more fully engage water users, managers, and stakeholders in its collaborative State water management approach.

The rapidly evolving science and practice of climate change assessments warranted collaboration and participation with other organizations focused on potential climate change impacts to water resources management and direct involvement in other related intrastate programs and projects.

CRWAS outreach activities included meetings, presentations, and workshops with:

- CWCB Board of Directors
- CWCB, DNR, DWR, and AG Staff
- CWCB CCTAG
- Interbasin Compact Committee (IBCC) and IBCC BRTs
- Joint Front Range Climate Change Vulnerability Study (JFRCCVS) Program
- NOAA Regional Integrated Sciences and Assessments (RISA) Program
- University of Colorado's Western Water Assessment (WWA) Program
- Northern Colorado Water Conservancy District (Water User Meeting)
- Colorado River Water Conservation District (Annual Water Meeting)
- Colorado House-Senate Joint Agriculture Committee
- Front Range Water Council
- Colorado Water Congress

Where to find more detailed information:

Outreach presentations and newsletters associated with CRWAS Task 1.1 – *Start-up, Coordination, and Reporting*, CRWAS Task 1.2 – *IBCC / BRT Meetings*, CRWAS Task 1.3 – *Public Information*, CRWAS Task 4.2 / 5.2 – *BRT Workshop Presentations*, CRWAS Task 7.1 – *Coordination with Front Range Vulnerability Study*, and CRWAS Task 7.13 – *Coordination with CWCB CCTAG* are available at http://cwcb.state.co.us/.

2.2.3 Coordination with Other State-Sponsored Programs

Throughout the CRWAS process, proposed methods of detailed analysis were presented in task memoranda reviewed with the appropriate sections within the CWCB, with the CCTAG, and with the other external reviewers including BRT members. The task memoranda were posted on the CWCB website and, as the Study Team has prepared responses to comments on the initial draft of the CRWAS (the March 2010 draft report) additional refinements have been made to many of the task memoranda. For readers interested in more detail, the revised Task Memoranda are again posted on the CWCB website.

In addition to the coordination of proposed study methods in the task memoranda, the CRWAS approaches and draft results were presented at numerous CWCB, IBCC, BRT and other types of meetings engaging a broad range of interests. These outreach efforts and the other studies and programs with which the CRWAS Study Team coordinated activities are presented in preceding section of this report.

As shown in Figure 2-2, there are many ongoing programs and processes that the CWCB performs or directs in close collaboration with other State agencies and programs. In addition to other State, federal and local agencies, the CWCB is coordinated closely with the IBCC and BRTs in reviewing the Study's methods and results.

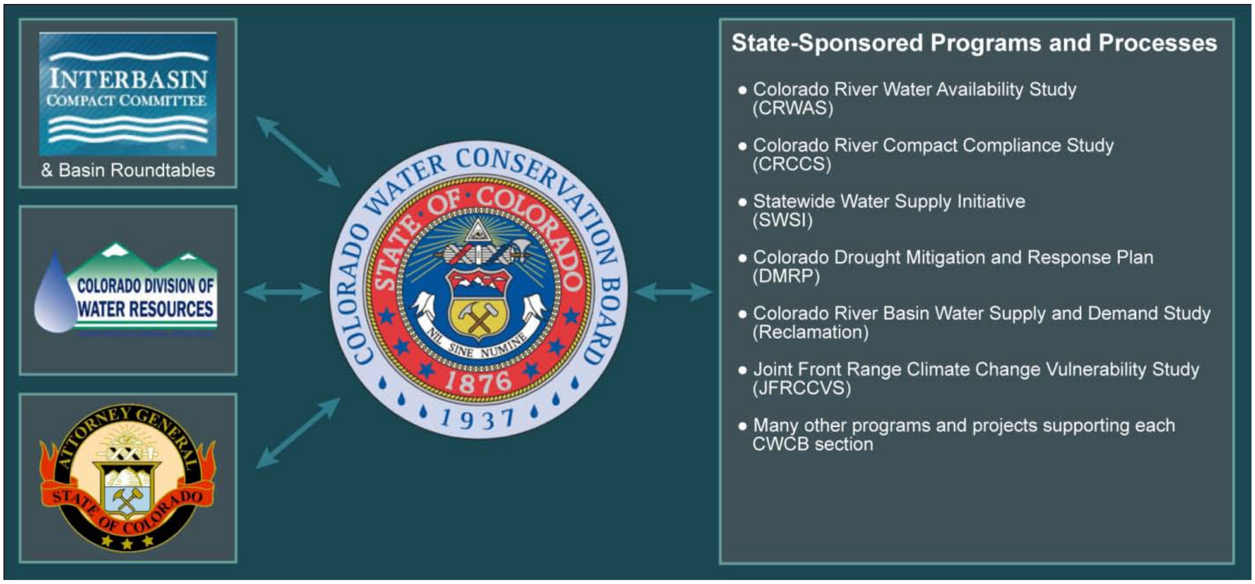


Figure 2-2 – State-Sponsored Water Management Programs Supported by the CRWAS

2.2.4 Refinements to State Water Planning Models

The CRWAS leveraged the State's investment in the CDSS modeling tools. Through extensive public outreach and direct collaboration with water suppliers and managers, the models were reviewed and refined to further enhance general confidence in the models' ability to simulate streamflows and project operations, and to provide important information for future assessments of non-consumptive water needs. The refinements were thoroughly documented to support subsequent CRWAS phases and other future State water resource modeling and planning initiatives. The CDSS proved fully capable of simulating current water uses (demands) and alternate hydrologic cases to provide a broad range of results including physical streamflow, consumptive use, and water available to meet future demands throughout the Study Area under Colorado's Prior-Appropriation Doctrine.

2.2.5 Forest Change

Forest disturbance, such as forest fire, disease, or logging may cause an increase in runoff volume[1] because less precipitation is lost through the processes of evaporation and plant transpiration. Sub-alpine zone (elevation greater than approximately 8,500 feet) forests are known to contribute most of the run-off (MacDonald, 2003). At lower elevations, annual precipitation decreases, and there is sufficient evaporation, soil water storage, and plant

[1] In addition, forest disturbance can impact the timing and rate of snow pack and snow melt (earlier peak flows) and water quality.

transpiration processes such that there is practically no change in the volume of runoff. Forest disturbance below the sub-alpine zone has almost no effect on the quantity of runoff (MacDonald, 2003).

Empirical information regarding forest disturbance indicate at least a 20 to 30 percent reduction in forest basal area is necessary before any increase in annual water yield can be detected (Douglass and Swank 1972, Bosch and Hewlett 1982, Hornbeck et al 1997). At the scale of a small or moderately sized basin, a fire devastating 30 percent or more of the trees is conceivable. However, disturbance from fires large enough to affect the larger basin are not expected. Consequently, the analysis of fire disturbance is not recommended as a component of the hydrologic runoff modeling regarding forest disturbance mechanisms.

Beetle kill of Colorado's mature lodge pole pine forests exemplify forest change on a large scale (basin wide). Forest officials report that the cumulative impacted area covers 1.9 million acres (US Forest Service and Colorado State Forest Service, 2009). Infestation primarily kills mature (>80 years old and >8 inches in diameter) lodge pole pine trees (Aguayo, 2006), with smaller trees also being infested and killed on a smaller scale. Researchers predict that the epidemic may infect nearly every mature lodge pole pine forest in the State.

Temporary increases in water yield are expected from watersheds with beetle kill in even-aged stands of lodge pole pine trees (Stednick, PowerPoint). No increase in water yield is expected from uneven aged stands of trees because of regeneration or release of the understory. The hydrologic effects decrease over time as the understory and trees grow back. Because of the relatively low sensitivity of flow to clearing, and the notion that substantial vegetative recovery will occur over a period of a few decades, results of the deforestation analysis will have limited value for the two planning horizons (2040 and 2070) adopted for CRWAS.

The preferred technical approach to represent the short-term impact of forest disturbance is the use of hydrology modeling, and to be consistent with the other CWRAS efforts, the use of the Variable Infiltration Capacity (VIC) model. The model area would include the Colorado River Basin within Colorado and the scale of forest disturbance would be the area occupied by lodge pole pine. The change in run-off predicted by the VIC model could then be compared to empirical ranges described by MacDonald (2003) and others.

The technical approach would include adjusting vegetation parameters within VIC cells to reflect forest change due to insect infestation. The total area of potentially impacted tree types in each VIC grid cell, as a fraction of the total coniferous forest, would be estimated. The vegetation parameters in VIC would then be adjusted to reflect tree mortality on an area basis by reducing the coniferous forest fraction in the VIC vegetation parameter input to reflect elimination of potentially impacted tree types. The percentage of grass or understory vegetation types would be increased to reflect replacement of potentially impacted tree types by other vegetation.

Because the recovery time is expected to occur within a few decades, an analysis of deforestation is expected to have limited value for the CRWAS planning horizons, therefore the recommended approach was not included as part of CRWAS. At this time, the U.S. Forest Service, in conjunction with the CWCB and the North Platte River Basin Roundtable, is completing a multi-year study to collect information regarding forest change processes that most influence the hydrology of disturbed forests within Colorado. Information from the study is expected to better describe corresponding hydrologic processes, and to constrain assumptions to be used in future hydrological models. It may be appropriate to monitor this and other ongoing research in order to re-assess the potential for quantifying the impact of forest change when the results of that ongoing work become available.

Where to find more detailed information:

CRWAS Task 7.3 / 7.4 – *Forest Change Literature Review and Suggested Methods* technical memo is available at http://cwcb.state.co.us/.

2.2.6 Colorado River Compact

Sections 2.6 and 3.9 of the March 2010 Draft CRWAS Phase I Report (Draft Report) provided quantitative estimates of the amount of consumptive use, above existing levels, that can occur within Colorado under certain broad Compact assumptions ("water available for future consumptive use"). These estimates, and the description of the approach used to develop them, were the subject of the largest number of oral and written comments received following publication of the Draft Report. After careful consideration of the public comments, the Study Team, the CWCB and its staff agreed that Section 2.6 and Section 3.9 of the Draft Report would be replaced with the following summary of the complexities, challenges, and uncertainties inherent in making an estimate of potential water available for future consumptive use and in understanding how that estimate might affect Colorado water rights.

Summary of Comments

The CWCB and the CRWAS Study Team conducted multiple rounds of public outreach following release of the Draft Report; written public comments on the Draft Report were solicited immediately after its release, and public meetings were held with each of the BRT that requested such meetings.

The comments directed at Draft Report Sections 2.6 and 3.9 can be described in broad categories:

- *Remove Sections 2.6 and 3.9*. A number of entities suggested that Sections 2.6 and 3.9 not be included in the Final CRWAS Phase I Report. This suggestion was motivated primarily by the following issues.

    - *The range of water availability is too large to be useful*. Quantitative estimates of water available for future consumptive use were based on several broad assumptions about interpretations of the Colorado River Compact and the Upper Colorado River Basin Compact and on projections of future hydrologic conditions, which are also based on certain assumptions. These legal and hydrologic uncertainties, which are addressed in more detail below, led to a range of results that, in the view of many of the entities, did not enhance understanding of the constraints that may be imposed on future Colorado water uses.

    - *The Draft Report did not explain the approach in enough detail.* There is a general concern that alternative interpretations of the Colorado River Compact and the Upper Colorado River Basin Compact will be the subject of future litigation or sensitive negotiations motivated by the prospect of litigation. In view of this concern, the State of Colorado is taking a cautious approach when framing assumptions, even for general planning studies, that might be argued to be an official position of the State. As such, the descriptions of the approach used in developing estimates of water available for future consumptive use were necessarily general in nature so some readers of the Draft Report expressed difficulty evaluating the approach.

- *The Draft Report did not explain how estimates of water available for future consumptive use would translate into yields of Colorado water rights.* Estimates of water available for future consumptive use may imply a reduction in consumptive use within Colorado compared to levels estimated assuming only intra-state administration of water rights. In order to develop estimates of the yields of individual water rights under the assumption that such a constrained condition is in effect, it would be necessary to make assumptions about the intra-state rules by which a possible curtailment would be administered. Development of such assumptions was not within the scope of the Study.

CWCB Board members expressed similar opinions to those offered by the public and other agencies, and suggested that it may be appropriate to conduct a more complex analysis outside of this study.

Questions regarding Interpretation of Compacts

One of the factors that contributed to the wide range of estimates of water available for future consumptive use is the ongoing uncertainty regarding interpretation of several provisions of the Colorado River Compact and the Upper Colorado River Basin Compact. This section provides a brief summary of the primary, relevant provisions of the Colorado River Compact and the Upper Colorado River Basin Compact, and highlights some of the potentially unresolved interpretations of those provisions.

The Colorado River Compact of 1922 did not apportion water directly among states. Instead, the Compact divided the river into the Upper Basin, above Lee Ferry, Arizona, and the Lower Basin below Lee Ferry and apportioned, in perpetuity, the consumptive beneficial use of water to equal amounts of 7.5 million acre-feet (maf) per annum, for each of the two basins. It also set out an obligation of the states of Colorado, New Mexico, Utah and Wyoming ("states of the Upper Division") not to deplete flows passing Lee Ferry below 75 maf in any running ten year period and specified how water obligations to Mexico would be met. Significant provisions of the Colorado River Compact in relation to the CRWAS include:

- Article III(a) - grants a perpetual right to beneficial consumptive use of up to 7.5 maf per year to both the Upper Basin and the Lower Basin, respectively.

- Article III(b) - allows the Lower Basin to increase its beneficial consumptive use from the Colorado River system by up to one maf/year.

- Article III(c) – anticipates how a water obligation to Mexico would be met if the United States entered a treaty regarding use of Colorado River water with Mexico (which it did in 1944).

- Article III(d) - requires that the states of the Upper Division not cause the flow passing Lee Ferry to be depleted below 75 maf in any consecutive 10-year period.

- Article VIII - provides that “present perfected rights to the beneficial use of waters of the Colorado River system” are unimpaired by this compact.

The Upper Colorado River Basin Compact apportions water among the states in the Upper Basin: Arizona, Colorado, New Mexico, Utah and Wyoming. The Upper Colorado River Basin Compact allocates use of water in the Upper Basin on a percentage basis (except for Arizona, which was apportioned 50,000 acre-feet of consumptive use per year). Significant provisions of the Upper Colorado River Basin Compact include:

- Article III - apportions consumptive use of water to the Upper Basin States. After Arizona’s fixed apportionment, the remainder of the beneficial consumptive use available to the Upper Basin is allocated as follows: Colorado, 51.75 percent; New Mexico, 11.25 percent; Utah, 23 percent; and Wyoming, 14 percent.

- Article IV - specifies “principles” that the Upper Colorado River Commission will apply “in the event [that] curtailment of use of water” becomes “necessary in order that the flow at Lee Ferry [is not] depleted below that required by Article III of” the Colorado River Compact. One of these “principles” is established in Article IV(b), which provides that if an Upper Division State has used more water than it is apportioned in the ten years before a curtailment, then the overusing State will ”pay back” the amount of overuse (by supplying an amount of water equal to its overuse at Lee Ferry) before “demand is made on any other” Upper Division State. Article IV(c) establishes another “principle” for the Upper Colorado River Commission to apply in curtailment determinations, that except as provided in Art. IV(b) relating to overuse and “pay back,” the extent of any curtailments will be made in proportion to each state’s consumptive use in the preceding water year. Article IV also specifically excludes uses under water rights perfected prior to November 22, 1922 (the date on which the Colorado River Compact was signed) from this calculation. Subsequent litigation has provided additional information regarding present perfected rights.

There are many unsettled issues of interpretation of both compacts. Unsettled provisions of the Colorado River Compact include, but are not limited to:

- The definition of present perfected rights. The Colorado River Compact recognized present perfected rights but did not provide a definition of those rights. In Arizona v. California, the U.S. Supreme Court defined the meaning of “present perfected rights” under the Boulder Canyon Project Act, which apportioned use of Colorado River water within the Lower Basin. In this decision, the Court established that a “present perfected right” included rights put to beneficial use as of June 25, 1929, the effective date of the Boulder Canyon Project Act, which in addition to making Lower Basin apportionments also made the Colorado River Compact effective. The Court’s decision in Arizona v. California is based on interpretation of the Boulder Canyon Project Act, and not the Colorado River Compact, therefore, the Court’s definition of “present perfected rights” has not been made applicable to the Colorado River Compact. In addition to June 25, 1929, other dates that have been considered to apply to “present perfected rights” include November 24, 1922, the date the Colorado River Compact was signed and the date referenced in the Upper Colorado River Basin Compact Art. IV(c), or February 24, 1944, the date on which the Arizona state legislature ratified the Compact.

- Identification and quantification of Colorado’s present perfected rights.

- Quantification of tributary flows in the Lower Basin as part of the Colorado River System. The Colorado River System is defined in Article II of the Colorado River Compact to include the Colorado River and its tributaries. Although the Supreme Court decree in Arizona v. California established rights to the use of water from the tributaries of the Lower Basin under the Boulder Canyon Project Act, it declined to find whether apportionments in the Colorado River Compact include tributaries, or just the mainstream. The Upper Division states maintain that the tributaries need to be included in any system accounting for purposes of calculating surplus because this affects the determination of any requirement on the part of the Upper Basin to share in the obligation to Mexico.

- Compact accounting of consumptive use from the Colorado River system in the Lower Basin. Quantification of the natural flow of Lower Basin tributaries will require accounting of consumptive use on those tributaries.

- How to define and measure a “deficiency” in system surplus under Article III(c) of the Colorado River Compact. If a surplus is insufficient to meet the United States’ obligation to deliver Colorado River water to Mexico under the treaty, the Upper Basin and Lower Basin are to bear this “deficiency” equally. Article III(c) of the Colorado River Compact requires that the treaty obligation to Mexico first be supplied from waters that are surplus to the quantities set out in Art. III(a) and (b). Only if the surplus is insufficient to meet the Mexico obligation is the Upper Basin required to bear one-half of any deficiency. Because of the lack of information about the quantification of Lower Basin tributary flows, any obligation of the Upper Basin cannot be precisely quantified at this time.

- Provisions in the Mexico Treaty that may reduce the treaty obligation during “extraordinary droughts.” Article 10 of the 1944 treaty with Mexico provides for a reduction in the annual delivery of 1.5 maf in proportion to reductions in consumptive uses in the U.S. in the event of “…extraordinary drought or serious accident to the irrigation system in the United States…”. A comparable “extraordinary drought” provision is referred to in the Rio Grande section of the same 1944 Treaty. Because “extraordinary drought” is not defined in either the Colorado River or Rio Grande sections of the Treaty, uncertainty exists about how a treaty interpretation of “extraordinary drought” would be implemented between the United States and Mexico.

Unanswered questions raised by the Upper Colorado River Basin Compact include how curtailment provisions in the compact will be interpreted and administered, including the possibility that the Upper Colorado River Commission may adopt rules or operating principles regarding certain curtailment issues and how these rules or operating principles would apply to the Upper Division States. Examples of the remaining questions regarding how curtailment provisions may be interpreted or administered include, but are not limited to:

- *Method of calculating consumptive use.*

- *Basis for curtailment*. After all overuse has been offset, additional curtailments are made in proportion to each state’s consumptive use in the preceding water year. This means that Colorado’s share of any remaining curtailment is not a fixed value (i.e., its apportionment of 51.75 percent), but an amount that depends on Colorado’s actual consumptive use of Colorado River water in relation to the other Upper Division State’s actual consumptive uses.

- *Questions regarding the definition and quantification of present perfected rights in the Upper Basin*. Present perfected rights are not subject to curtailment and are not to be included in the calculation of a State's consumptive use for determining a State's share of any curtailment or a 'pay back' obligation.

- *Questions regarding whether and how overuse from the system should be paid back before other states are required to curtail.*

In addition, the integration of tribal water rights into compact administration remains the subject of a legal debate.

These legal unknowns and uncertainties in both Compacts will not be reduced until they are negotiated, litigated or both.

Uncertainties in Intra-State Water Administration

A number of comments stated that the Draft Report did not explain how estimates of water available for future consumptive use would translate into yields of Colorado water rights. Estimates of the effect of potential Compact constraints on the yield of individual Colorado water rights are affected by assumptions regarding the nature of the intra-state rules that might be used to administer such a curtailment, requiring corresponding analysis to adopt assumptions about these rules. Administrative rules that are adopted in the future will be the result of a rule-making and may subsequently be shaped by litigation. The outcome of the rulemaking and litigation processes cannot be predicted with certainty.

The Colorado River Compact Compliance Study (CRCCS), being conducted by the CWCB, will begin to identify issues associated with the administration of state water rights in the Colorado River basin under the terms of the Colorado River Compact and Upper Colorado River Basin Compact. The CRCCS is anticipated to begin identifying, developing and evaluating possible approaches to intra-state administration of Colorado River water rights, if a curtailment of uses of Colorado River water is deemed necessary by the State of Colorado in order for the State to comply with its obligations under the Colorado River Compact and the Upper Colorado River Basin Compact. The work of the CRWAS Phase I Report is expected to serve as a data source to help inform activities associated with the CRCCS.

Uncertainties in Future Hydrologic and Climatic Conditions

The principal source of uncertainty across projections of future hydrologic conditions comes from the global climate models, and these uncertainties are unlikely to be reduced in the near future. Uncertainty inherent to projected climate results in corresponding uncertainty in projected estimates of future natural flow and water use, which, in turn, creates uncertainty in estimates of the amount of water available for future consumptive use. This uncertainty is likely to be as large or larger than, the effect of uncertainty surrounding the legal provisions of the Compacts.

Summary

Unanswered questions arising from legal interpretations of the Colorado River Compact and the Upper Colorado River Basin Compact are significant. Uncertainties inherent in projecting future hydrologic conditions are similar in magnitude to the effect of the unanswered legal questions. The compounded effects of these sources of uncertainty led to a range of possible futures that were viewed as unacceptable by many of those who commented on the March 2010 Draft CRWAS Phase I Report. Comments also expressed concern about the degree of simplification and the lack of transparency in the approach that was adopted to simulate the complex legal and hydrologic system. In addition, at this time the exploration of possible curtailment administration options is just beginning, and it is difficult to predict how any future rules adopted by the State Engineer's Office may be developed and if, or how, they may evolve through litigation. Finally, there remain unsettled issues of interpretation of provisions of the Colorado River Compact, the 1944 Water Treaty with Mexico and the Upper Colorado River Basin Compact that may be the subject of litigation in the future. Because there may be sensitive interstate negotiations framed by potential future litigation, the State of Colorado prefers to avoid making assumptions about unanswered legal questions in a manner that may negatively affect Colorado's interests in the Colorado River by unintentionally compromising Colorado's negotiation, litigation and/or administrative options. Accordingly, the CWCB has determined that it is not appropriate to finalize quantification of the effect of Compact constraints on water availability to water rights in Colorado through this study at this time.

Where to find more detailed information:

For a description of the history of the compact and its provisions, the reader is directed to the *Citizen's Guide to Colorado's Interstate Compacts* and the references therein, published by the Colorado Foundation for Water Education, and to the full text of all of Colorado's interstate compacts on the CWCB web site: http://cwcb.state.co.us/legal/Pages/InterstateCompacts.aspx

2.2.7 Uncertainty in Water Supply Planning

Uncertainty is a very broad term that encompasses many concepts in our work and daily activities. In water resources, three different types of uncertainty are apparent, (1) that arising from the random nature of events, (2) that arising from the indefiniteness of measurements, and (3) that arising from imperfections in our state of knowledge.

1. Water resource managers and stakeholders continually deal with the random nature of events; a common example is the question, "how much water will there be in the river next year?" They also understand that our experience of droughts and wet spells cannot fully contain what the future may bring—deeper and longer droughts and more productive and longer wet spells will be encountered. While the consequences of this type of uncertainty can be costly, the water community is relatively comfortable living with it because of the continual reminders of its presence.

2. In the same way, those who work in the field of water resources have become relatively comfortable with the indefiniteness of measurements. Any measurement will vary from the "true value" of the thing being measured and the amount of that difference will depend on the tools and skills available to the person making the measurement. Estimates based on simulations will vary more than actual measurements.

3. The third type of uncertainty arises from imperfections in our state of knowledge: for example, we don't know exactly how the physical and physiological processes that cause evapotranspiration work; we don't have perfect means of simulating those processes, we don't know exactly what state of growth the plant is in, and we don't know exactly what the conditions are in the environment around the plant. Despite all these

uncertainties, the water community has also become relatively comfortable with methods to estimate consumptive use.

Nowhere do imperfections in the state of knowledge play a larger role than in making estimates of future conditions. For the last century or more, water resources management has been based on the understanding that the past was a good guide to the future. However, science has developed a new understanding of changes in the atmosphere that are likely to cause increased temperature in the Study Area. But estimates of how much temperature might change or what the consequences of those changes would be for water supply are highly uncertain; imperfections exist in the understanding of economic, political and physical processes, the ability to simulate those processes and the knowledge of current conditions These uncertainties cannot themselves be known completely, but research indicates that they are larger than any of the more familiar sources of uncertainty.

Estimating the water supply effects of future climate conditions requires combinations of several elements. For example, estimates of future temperature and precipitation must be utilized in a model that simulates crop consumptive use to estimate future agricultural water demands. When elements of an analysis are combined, their uncertainties carry into the result, but the individual uncertainties do not generally add up in a straightforward way, and overall uncertainty cannot be determined by a simple calculation. However, individual uncertainties do interact and each added element does increase overall uncertainty of the estimate of impact. This should be kept in mind when using projections of water availability based on the climate-adjusted hydrology.

CRWAS applied techniques to reduce uncertainty where this was practical, for example by using climate projections that have been calibrated and “bias-corrected” against historic conditions and by adopting techniques that makes much of the uncertainty in climate projections apparent, as is described more completely in the following sections.

Furthermore, uncertainties arising in the CDSS models, StateMod and StateCU and the VIC hydrology model have been minimized through extensive calibration and review. The CDSS models have been productively used to support the State’s water resource planning activities for more than 20 years and the State’s continuing process of model refinement assures that new data and operational procedures are continuously integrated. The VIC model was selected, among other reasons, based on previous independent calibration by others for Colorado River basin applications.

In summary, while uncertainty will always be a factor in water supply planning, the CRWAS tools and approaches minimize uncertainty to the maximum practical degree. Remaining uncertainty and the range of hydrologic results associated with projecting future climate conditions is a direct result of the uncertainties in future greenhouse gas emissions and uncertainties in the ability of models to simulate the effects of these emissions in the context of global atmospheric circulation.

Where to find more detailed information:

- For more information on climate change in Colorado: *Climate Change in Colorado, A Synthesis to Support Water Resources Management and Adaptation* (Ray et al., 2008), prepared for the CWCB, provides a great deal of valuable information about Colorado's climate, climate science, and projected climate conditions in Colorado. It provides particularly valuable descriptions of greenhouse gas emission scenarios and global climate models (http://cwcb.state.co.us/).
- For more information on climate models and downscaling:, *Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change,* published by the Water Utility Climate Alliance (WUCA) (http://www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf)
- For more information on approaches to planning under uncertainty: *Decision Support Planning Methods: Incorporating Uncertainties into Water Planning,* published by WUCA (http://www.wucaonline.org/assets/pdf/pubs_whitepaper_012110.pdf) and *Nonstationary Water Planning: An Overview of Several Promising Planning Methods,* by Marc Waage and Laurna Kaatz, published in the Journal of the American Water Resources Association, June, 2011.

2.3 Technical Approach

Technical activities of the CRWAS involve using a set of analytical tools to evaluate water availability for alternative hydrologic cases as described in this section. The tools and methods used in the CRWAS are among the most sophisticated and rigorous available to water supply planners anywhere and reduce uncertainty to the extent possible given the current state of scientific knowledge and the analytical tools available for water availability studies.

2.3.1 *Technical Approach Overview*

Phase I of the CRWAS evaluates water availability using the five step approach as shown in Table 2-1.

Table 2-1 – Phase I Technical Approach Summary

Historical Hydrology	**Data and Tools:** CDSS (StateCU and CDSS Natural Flows) **Results:** Historical Natural Flows, Modeled Streamflows, Consumptive Use, Reservoir Levels and Water Availability **Includes natural flow hydrology observed for period 1950–2005**
Extended Historical Hydrology	**Data and Tools:** Extending Paleo Datasets **Results:** Extended Natural Flows, and Wet/Dry Spell Statistics **Extended record dating from AD 762 (more than 1,200 years)** • Provides estimated natural flow traces. Flow magnitudes taken from historic flow record (1950-2005). • Flow sequences developed using statistical models applied to tree-ring data. • Provides a wider variety of year-to-year flow sequences than historical record. • Re-sequencing – Future sequences of wet and dry years cannot be predicted; therefore, 100 different 56-year hydrologic traces were developed. All are considered equally probable.
Climate-Adjusted Hydrology	**Data and Tools:** Variable Infiltration Capacity (VIC) Model **Results:** Climate-Adjusted Temperature, Precipitation, and Natural Flows **Based on the selection of five climate projections for each of the 2040 and 2070 planning horizons** • Used same five 2040 projections selected in the JFRCCVS; however, obtaining five appropriately distributed projections for CRWAS study conditions required different projections for 2070. • Each of the selected downscaled climate projections is treated as equally probable. • Temperature and precipitation changes were translated into effects on natural flow using the VIC hydrologic model. Flow sequences (dry/wet spells) were derived from those seen in the paleohydrology flow record.

Table 2-1 – Phase I Technical Approach Summary (cont.)

Climate-Adjusted Irrigation Demands	**Data and Tools:** CDSS (StateCU) **Results:** Climate-Adjusted Irrigation Demands **Superimposes historical or projected mean monthly temperature and total monthly precipitation on current irrigated acreage and crop types to estimate CIR.** • StateCU uses temperature-based monthly Blaney-Criddle approach, incorporating available locally calibrated coefficients to determine CIR. • Temperature triggers allow growing season start and end dates to reflect changes under varying climate conditions.
Water Allocation Modeling	**Data and Tools:** CDSS (StateMod) **Results:** Climate-Adjusted Streamflow, Water Availability, Reservoir Operations, and Consumptive Use **Reflects historical or projected climate-based natural flows, crop demands, and irrigation head gate demands.** • Uses current M&I demands, transmountain exports, reservoir capacities, and basin operations. • StateMod allocates historical or projected natural flows to meet demands based on Colorado water rights, current administrative agreements, and current reservoir operations. • Model provides physical streamflow and water available for future demands at 2,000+ locations throughout the Study Area. Includes reservoir use, diversions, and consumptive use.

Presented below are sections describing the application of analytical tools used in the modeling of water availability for Phase I of the CRWAS beginning with the Variable Infiltration Capacity (VIC) hydrology model and continuing with several sections on the CDSS tools.

Variable Infiltration Capacity (VIC) Hydrology Model

Hydrology models simulate the physical processes that operate on precipitation in the hydrologic cycle. These processes include those that move liquid water from the top of the vegetation or from the ground surface into water courses, either along the surface of the earth or through soils. Hydrology models also simulate evaporative processes, either direct evaporation from soil or open water surfaces, or transpiration of water through plants. Hydrology models are used in CRWAS to simulate the impact of projected changes in temperature and precipitation on natural streamflows. Natural flows are the flows that would have occurred absent man-caused changes, such as reservoir storage and releases or diversions and return flows.

Hydrology models are different from water resources system models (also known as water allocation models), such as the CDSS StateMod model, which begin with natural flows and simulate the movement of water through natural and man-made conveyances and storage facilities subject to human management decisions. Water allocation models are described further below.

The Variable Infiltration Capacity (VIC) hydrology model was used to quantify the effect of projected changes in climate on naturalized streamflow, required as input to the CDSS models. The VIC model has several applications to climate change studies and successful application to numerous basins around the world. It operates on a daily time step. It has a number of favorable attributes for the Study, but VIC's three most significant advantages are that it has a reliable, physically-based model of evapotranspiration, it has a physically-based model of snow dynamics, and it has been used for two studies of climate change in the Colorado River Basin for which calibrated parameters are available.

Evapotranspiration (ET) is the most significant water loss process in the hydrologic water balance. As such, the reliability of a hydrology model is directly related to the accuracy and reliability of the representation of ET. In mountainous terrain such as constitutes much of the significant water-producing areas of the Colorado River basin, physically-based ET models, like the ET model used in VIC, are preferred for basin-scale analyses where local calibration of vegetation coefficients is not feasible.

Snow accumulation and snow melt are also important processes in simulating the seasonal pattern of streamflow. Because all of the available projections of future climate show that temperature will increase, changes in the seasonal pattern of snow accumulation and melt will result. A more physically-based snow model, of the sort used in VIC, provides more confidence that simulations involving changes in temperature will result in realistic changes in snow accumulation and snow melt.

Colorado Decision Support System

Water availability under historical and projected climate conditions was estimated using tools developed for the statewide CDSS. CDSS was developed by the CWCB with support from the Colorado Division of Water Resources and consists of a database of hydrologic and administrative information related to water use in Colorado, and a variety of tools and models for reviewing, reporting, and analyzing the data. Historical water-related data, including stream flows, diversions, water rights, climate records, and reservoir contents, are stored in a central database called HydroBase. Spatial data, such as irrigated acreage and point locations of ditch head gates, stream flow gages, and climate stations, are also stored in HydroBase.

These underlying data were fundamental to the development of the Colorado-basin specific modeling tools available for use in the CRWAS. Data sets for the consumptive use model, StateCU, have been developed to represent historical use in each of the five major basins (Study Basins) that collectively make up the Colorado River Basin in Colorado; Yampa River basin, White River basin, Upper Colorado River basin, Gunnison River Basin, and the combined San Juan River and Dolores River basins. These data sets include current levels of irrigated acreage, crop types, and irrigation practices superimposed spatially on climate data for the 1950 through 2005 study period.

The CDSS water resources planning models are water allocation models, which determine availability of water to individual users and projects based on hydrology, water rights, and operating rules and practices. They are implementations of StateMod code developed by the State of Colorado for application in the CDSS project. StateMod is used to represent each basin's hydrology, demand, water rights, and operations. StateCU generates crop irrigation demand estimates that are used directly in the StateMod model. StateMod starts with hydrology then operates based on Colorado water right priorities to meet the irrigation, municipal, industrial, transbasin, storage, and instream flow demands.

CDSS planning models have been developed for each of the five study basins specifically for the types of basin-wide "what-if" analyses applications used in the CRWAS. The model data sets extend from 1950 through 2005 and simulate current demands, current infrastructure and projects, and the current state administrative environment as though they were in place throughout the modeled period. For the CRWAS study, StateMod is run on a monthly time-step. This is an appropriate time-step for planning purposes and coincides with the available data from the climate projections and the precision of the hydrology models. Note that the CDSS planning models do not reflect Colorado River Compact provisions and associated potential restrictions in the estimates of water availability; only the impacts due to current Colorado water uses and administration within the state are represented.

Figure 2-3 shows the general data-centered philosophy that governed the development of CDSS. As shown, information is stored in HydroBase and extracted for viewing, analysis, and use in subsequent modeling efforts through Data Management Interfaces (DMI). The data-centered approach allows input files developed for consumptive use and water resources planning models to be created and formatted in a consistent fashion, and updated easily when new data becomes available.

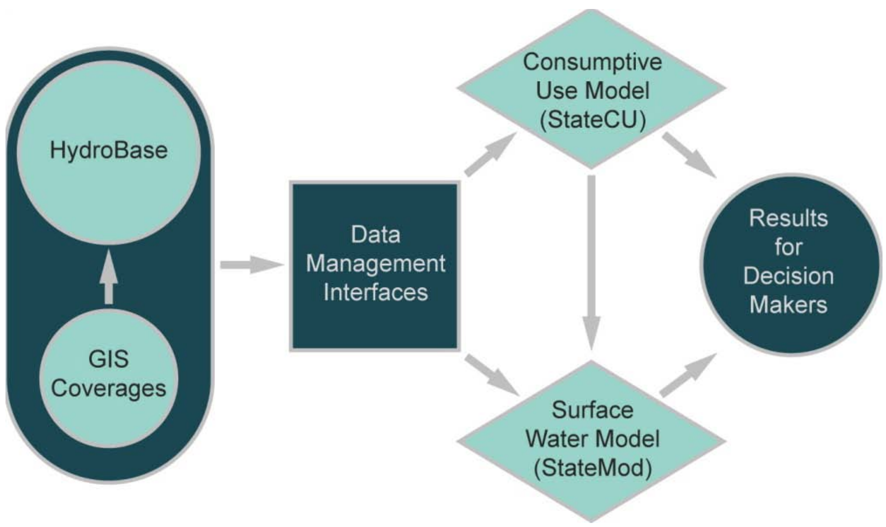


Figure 2-3 – CDSS Data-Centered Approach

The CDSS analysis models were developed as tools to test the impacts of changes to the current water resource systems, including potentially higher agricultural demands and varying natural hydrology due to projected climate changes. The models can simulate these potential changes constrained by current reservoir and diversion infrastructure, operations, and water rights administration. The models are publically available and have been reviewed, enhanced, and used to help in water resources planning decisions since development began in the early 1990s. The reliability and acceptance of the models, plus the ease in which model inputs can be revised due to the data-centered approach, make them the perfect tools to investigate the impact projected climate change may have on water available for future development in the Study basins.

Where to find more detailed information:

For more information on the CDSS development, see the Task 4.1 – *Overview of the CDSS* memorandum available on the Colorado River Water Availability link via the CWCB website (http://cwcb.state.co.us/). For summaries of the Study basin StateMod models, the Task 4.1 – *Modeling Briefs* are also available at that link. StateMod and StateCU data sets and full User Manual documentation can be downloaded, along with StateMod and StateCU executables, from the CDSS website (http://cdss.state.co.us/).

CRWAS outreach presentations of CDSS model review and refinement activities are provided in CRWAS Task 4.2 – *BRT Workshop Presentations* and CRWAS Task 5.2 – *BRT Workshop Presentations*, available at http://cwcb.state.co.us/.

Documentation of general background information on CDSS models is provided in CRWAS Task 4.1 – *CDSS Modeling Briefs.* Suggested enhancements and specific enhancements incorporated into the CDSS models are outlined in CRWAS Task 4.4 – *Recommended Model Refinements*, and documented in detail in the Model User's Manuals, available at http://cdss.state.co.us/.

StateMod and StateCU revised data sets and full User Manual documentation can be downloaded, along with StateMod and StateCU executables, from the CDSS website (http://cdss.state.co.us/).

CDSS Model Automation, Testing, and Presentation of Results

Thousands of CDSS model runs were executed in the Study to provide water users and providers with a range of results associated with alternate historical hydrology and projected climate hydrology. The DMI tools were run prior to each StateCU and StateMod model execution to generate the revised model input files, using the established CDSS standards. StateMod climate-based input files of CIR, head gate demands, and natural flows were re-sequenced to represent climate variability seen in the paleohydrologic record for the historical and projected climate analyses. In addition, StateMod results needed to be quickly reviewed for potential issues. Therefore, an automated procedure was developed to create the required new input files, to run StateCU and StateMod, and to graphically review the results.

StateCU generates CIR estimates for over 1,250 ditch structures and aggregated irrigation structures represented in the Study basin models for each month in the 1950 through 2005 study period. StateMod results for the Study basins are extensive and include simulated estimates of physically and legally available flow at more than 2,200 locations. In addition, StateMod results include information at each diversion node including demand, diversions from direct rights or from storage, consumptive use of diversions, and shortages. Results for each model run, and at each model location, are available via a web-viewing tool developed specifically for access to the CRWAS results (CRWAS Data Viewer).

For reporting purposes, it was necessary to identify a manageable subset of locations to view, analyze, and compare results. Results presented in the main body and appendices of this report represent historical hydrology and climate change hydrology based on the 1950 through 2005 period of climate variability. The results for re-sequenced historical and climate change hydrology can be accessed, viewed, and saved through the CRWAS Data Viewer. The following general criteria were used to select analysis locations presented in this report:

- Select locations that correspond to USGS stream gages
- Include locations in each of the five study basins
- Select locations that represent total tributary runoff (locations above river confluences)
- Include locations that represent critical areas (calling rights, for example near Shoshone Power Plant or near the Grand Valley Diversions in the upper Colorado River Basin)
- Consider locations below significant transbasin diversions or reservoirs
- Select locations that represent varying elevations
- Include locations that overlap with locations selected for presentation in the Front Range Vulnerability Study

Using the criteria, 42 locations were selected as shown in Table 2-2 and Figure 2-4. Four reservoirs that provide supplemental supplies primarily to meet irrigation demands within the Study basins were selected: Vega Reservoir, Yamcolo Reservoir, Ridgway Reservoir, and McPhee Reservoir. In addition, results are shown for Green Mountain Reservoir and Blue Mesa Reservoir, both multi-purpose reservoirs that include irrigation use. Water availability information for the following locations is provided within this report.

Table 2-2 – Locations for Results Analysis

Study Basin	*Location Description*	*USGS Gage ID*
UPPER COLORADO	COLORADO RIVER NEAR GRAND LAKE	09011000
UPPER COLORADO	MUDDY CREEK AT KREMMLING	09041500
UPPER COLORADO	BLUE RIVER BELOW DILLON	09050700
UPPER COLORADO	BLUE RIVER BELOW GREEN MOUNTAIN RES	09057500
UPPER COLORADO	EAGLE RIVER BELOW GYPSUM	09070000
UPPER COLORADO	COLORADO RIVER AT DOTSERO	09070500
UPPER COLORADO	ROARING FORK RIVER NEAR ASPEN	09073400
UPPER COLORADO	ROARING FORK RIVER AT GLENWOOD	09085000
UPPER COLORADO	COLORADO RIVER NEAR CAMEO	09095500
UPPER COLORADO	PLATEAU CREEK NEAR CAMEO	09105000
UPPER COLORADO	COLORADO RIVER NEAR CO-UT STATE LINE	09163500
GUNNISON	EAST RIVER AT ALMONT	09112500
GUNNISON	TAYLOR RIVER AT ALMONT	09110000
GUNNISON	TOMICHI CREEK AT GUNNISON	09119000
GUNNISON	GUNNISON RIVER NEAR GUNNISON	09114500
GUNNISON	CIMARRON RIVER AT CIMARRON	09126500
GUNNISON	GUNNISON RIVER BELOW GUNNISON TUNNEL	09128000

Study Basin	Location Description	USGS Gage ID
GUNNISON	GUNNISON RIVER NEAR LAZEAR	09136200
GUNNISON	UNCOMPAHGRE RIVER AT DELTA	09149500
GUNNISON	GUNNISON RIVER NEAR GRAND JUNCTION	09152500
SAN JUAN/DOLORES	SAN JUAN RIVER NEAR CARRACAS	09346400
SAN JUAN/DOLORES	PIEDRA RIVER NEAR ARBOLES	09349800
SAN JUAN/DOLORES	LOS PINOS RIVER AT LA BOCA	09354500
SAN JUAN/DOLORES	FLORIDA RIVER AT BONDAD	09363200
SAN JUAN/DOLORES	ANIMAS RIVER NEAR CEDAR HILL, NM	09363500
SAN JUAN/DOLORES	LA PLATA RIVER AT HESPERUS	09365500
SAN JUAN/DOLORES	LA PLATA RIVER AT CO-NM STATE LINE	09366500
SAN JUAN/DOLORES	MANCOS RIVER NEAR TOWAOC	09371000
SAN JUAN/DOLORES	DOLORES RIVER NEAR BEDROCK	09171100
SAN JUAN/DOLORES	SAN MIGUEL RIVER AT NATURITA	09175500
YAMPA	YAMPA RIVER BELOW STAGECOACH RES	09237500
YAMPA	ELK RIVER AT CLARK	09241000
YAMPA	ELKHEAD CREEK NEAR ELKHEAD	09245000
YAMPA	WILLIAMS FORK AT MOUTH, NEAR HAMILTON	09249750
YAMPA	YAMPA RIVER NEAR MAYBELL	09251000
YAMPA	LITTLE SNAKE RIVER NEAR LILY	09260000
YAMPA	YAMPA RIVER AT DEERLODGE PARK	09260050
WHITE	NORTH FORK WHITE RIVER AT BUFORD, CO	09303000
WHITE	SOUTH FORK WHITE RIVER AT BUFORD	09304000
WHITE	WHITE RIVER BELOW MEEKER	09304800
WHITE	PICEANCE CREEK AT WHITE RIVER	09306222
WHITE	WHITE RIVER NEAR CO-UT STATE LINE	09306395

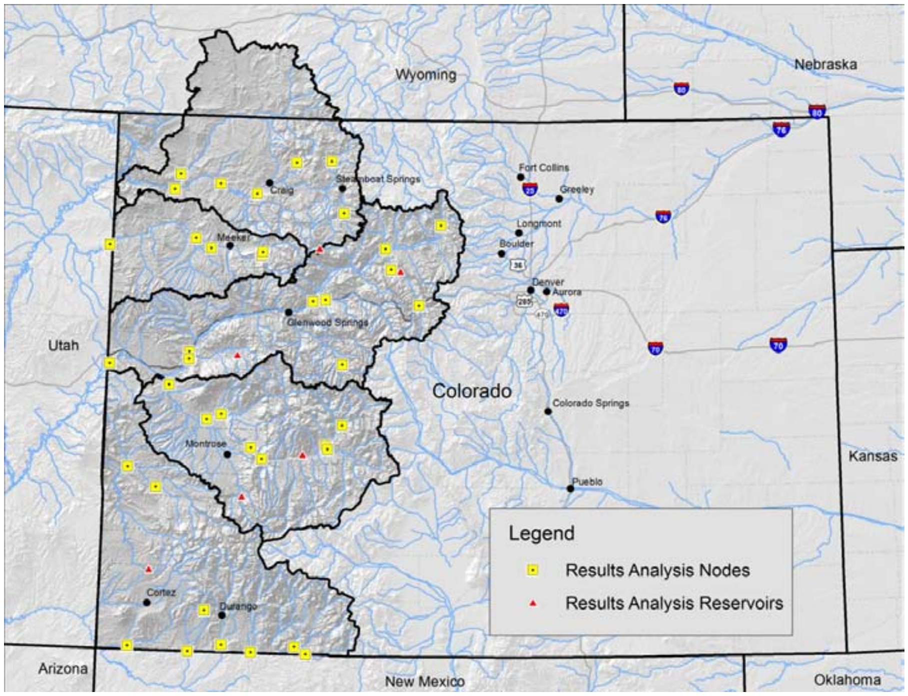


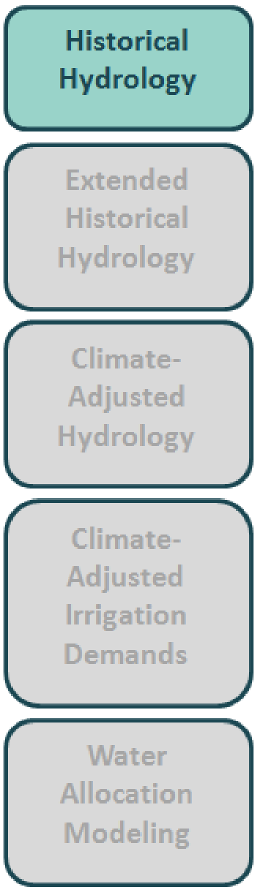
Figure 2-4 – Locations for Results Analysis

An automated data-centered approach was developed that incorporated temperature, precipitation, and natural flow data associated with the climate projections into StateCU and StateMod input files. To incorporate the information from the paleohydrologic record, the automated approach included re-sequencing of both historical climate-based input files. To simulate all the hydrologic cases 1,100 StateMod model runs were made for each basin (1,100 = 100 traces for extended historical climate conditions and 100 for each of the ten climate projections).

Where to find more detailed information:

The details of the automated, reproducible approach to develop input files and to simulate each of the 1,100 scenarios developed for each of the Study Basins are presented in the Task 6.6 / 7.11 – *CDSS Automation, Testing, and Application* memorandum available on the Colorado River Water Availability link via the CWCB website (http://cwcb.state.co.us/).

2.3.2 *Historical Hydrology*



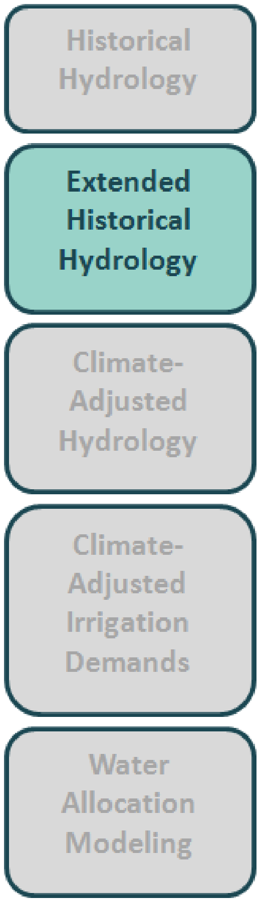
The historical hydrology consists of historical natural flows along with historical temperature and precipitation. The historical hydrology serves as the basis for development of extended hydrologic data that reflect more extreme droughts and wet spells contained in the prehistoric record of tree rings, (the Extended Historical Hydrology), and adjusted hydrologic data that reflect the impact of projected future climate (the Climate-Adjusted Hydrology). The Study historical period was defined to be the period from 1950 through 2005.

Historical natural flows represent historical hydrologic conditions absent the effects of man. All of the CRWAS water availability analyses have been anchored to historical natural flows: for the five study basins these are the CDSS naturalized flow (baseflow) data, which have been estimated for 227 headwater nodes and locations with significant inflow.

Natural flows have been calculated for CDSS using data on historical depletions and reservoir operations. StateMod automates the procedure by estimating natural flow time series at specified discrete inflow nodes where historical measured data is available by adding historical values of upstream depletive effects to the gaged value, and subtracting historical values of upstream augmenting effects from the gaged value as follows:

Historical diversions and reservoir contents, measured by the Division of Water Resources and stored in HydroBase, are provided directly to StateMod to make this computation. Evaporation is computed by StateMod based on historical evaporation rates and reservoir contents. Return flows are similarly computed based on diversions, crop water requirements, estimated delivery efficiencies, and return flow timing parameters. The process used to generate natural flows is described in Section 4 of the basin models' user manuals.

2.3.3 *Extended Historical Hydrology*



The CRWAS scope included development of a method to use information from prehistoric tree-ring records to extend observed records of flows (i.e., to develop an "extended historical hydrology") consisting of 100 traces, each 56 years in length. Collectively, such a set of traces is referred to as an "ensemble" of traces.

The approach used to extend historical hydrology is described in this section. Information from the tree-ring records was also used to extend the climate-adjusted natural flows, which reflect the impact of projected climate change. This was because there is evidence in the literature describing climate modeling to indicate that in some locations global climate models (GCMs) do not reliably replicate the year-to-year variability of climate and therefore hydrology.

The implications of wet and dry spells to water availability and project performance are best determined by simulation of specific water rights and structures, as is done with the CDSS models. Accordingly, the sequences of alternate historical hydrology were run through CDSS models so the output databases from those runs will reflect the impact of variability as captured in the alternate historical hydrology. These output databases are available to the public through the CRWAS Data Viewer. The computer time necessary to run the five CDSS basin models set a practical limit of 100 for the number of traces used in the alternate historical hydrology.

Re-sequencing Historical Hydrology

The overall context for extension of flows using paleohydrology is illustrated using Figure 2-5, a chart showing paleohydrologic reconstructed annual streamflow for the period 1600-2004 on the Colorado River at Lees Ferry, AZ, (Meko et al., 2007), along with the naturalized observed flows at that site (the complete reconstruction extends from A.D. 762; a shorter period is shown for clarity). The pre-observation period extends from 1600 until 1905. The period over which tree-ring chronologies overlap observed flows extends from 1906 through 2004 and is referred to as the overlap period. The reconstructions are based on a functional relationship, typically a linear regression, between tree-ring chronologies and the streamflows (e.g., Stockton, 1975; Stockton and Jacoby, 1976, Meko et al., 2007), developed over the overlap period, which is then used to estimate flows during the pre-observation period.

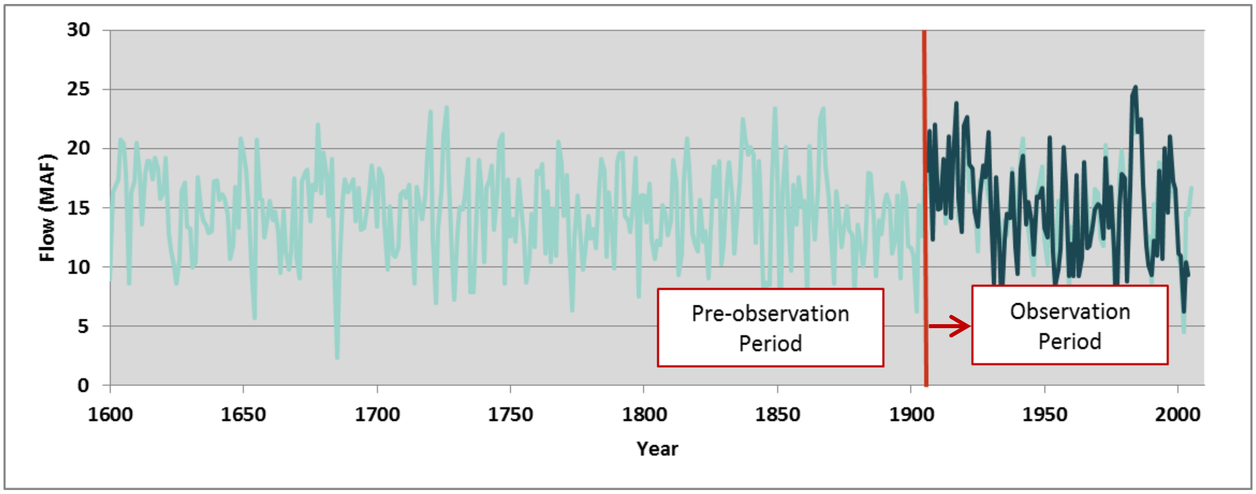


Figure 2-5 – Reconstruction of Colorado River Annual Flow at Lees Ferry

In the linear regression approach, a suite of trees are cored to obtain a record of tree-ring widths, which are corrected for physiological and other biases to obtain tree-ring growth indices[2]. Tree-ring growth indices for many trees at one site are typically aggregated (usually by averaging) into a chronology, which contains a single index value for each year in the chronology. A stepwise regression approach is used to select the best subset of tree-ring chronologies, based on the ability of that subset to predict streamflows at a specified location, and a multiple linear regression (MLR) model is fitted to the observed streamflow. This MLR model is then used to estimate streamflows during the pre-observation period using tree-ring chronologies. Variations of this basic approach have been proposed[3].

These reconstruction techniques, applied to the suite of available tree-ring information, capture very well the variability of the observed flow (i.e. what years are wet or dry), but the flow magnitudes generated by these techniques differ from one reconstruction to another in the pre-observation period. This can be seen in seven reconstructions of Lees Ferry flows (Stockton and Jacoby, 1976; Hidalgo et al., 2000, Woodhouse et al., 2006) shown in Figure 2-6.

[2] Trees actually add a *volume* of new growth each year and that volume varies depending on environmental conditions and other factors such as disease. As the tree diameter increases, a given volume of growth will be contained in a thinner ring. Thus, this geometric effect must be accounted for in the creation of tree-ring indices. Other effects also require compensation, such as autocorrelation caused by physiological factors such as energy storage.

[3] For instance, Hidalgo et al., (2000) used the MLR approach on the Principal Components (PC) of the tree-ring indices. The reconstructions in this approach are sensitive to the number of PCs retained, as shown by Hidalgo et al. (2000) in their comparison with traditional MLR-based reconstructions.

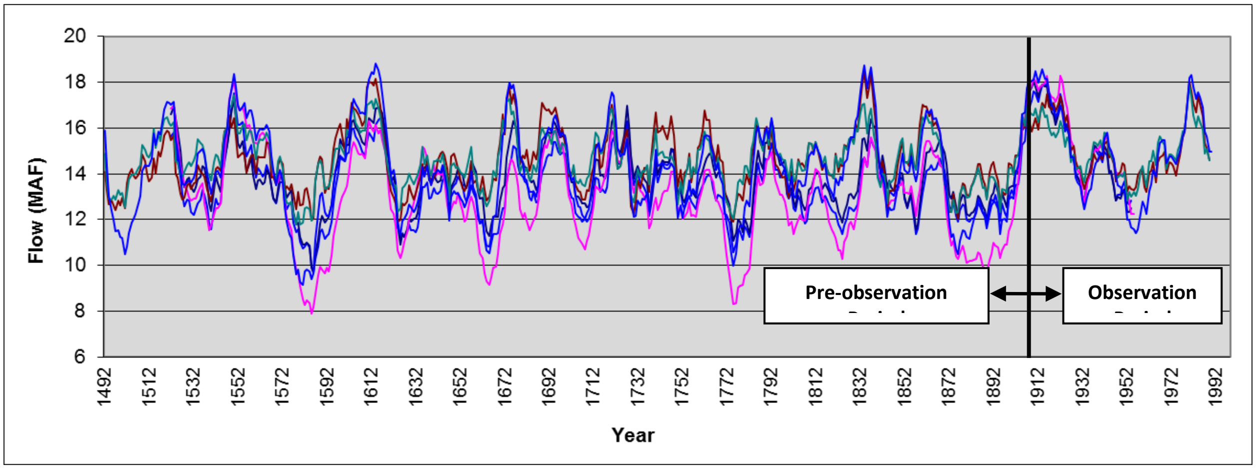


Figure 2-6 – Seven Reconstructions of Colorado River Annual Flow at Lees Ferry

The divergence of streamflows among the various reconstructions during the pre-observation period is due to the use of different reconstruction calibration techniques, different tree-ring data treatment, different tree-ring data, and different gage data (both the years used and the hydrologic time series itself) for the calibration. All of these are potential sources of the differences, and these differences should be expected. The fact that these different reconstructions show coherent wet and dry periods is a testament to the robustness of the hydroclimatic signal in the trees.

In recent years several statistical methods have become available that obtain information regarding the sequence of wet and dry states from the tree-ring record and sample flow magnitudes from the observed records.[4] For a more complete description of these methods the reader is referred to Gangopadhyay et al. (2008) and references contained therein.

Where to find more detailed information:

A literature review and evaluation of approaches for extending historical and climate adjusted hydrology are described in detail in CRWAS Technical Memorandum Task 6.1 / 6.2 / 6.3 – *Literature Review and Method Evaluation, Analyses of Tree-Ring Data, Recommendation for Extending Historical Hydrology*., available at http://cwcb.state.co.us/.

A method based on the approach developed by Prairie et al. (2008) was determined to be well-suited for creating input data sets for complex water resources models and was adopted for use in the Study. This approach was adopted for several reasons.   Most importantly, it was the most effective and cost effective method for blending drought intensity-duration-frequency information from the paleo record with the impact of projected climate, and it is the only available method that can extend estimates of water use while maintaining their correlation with streamflow. In addition, the approach has considerable credibility from its use in the recent model studies to develop guidelines for Lower Basin shortages and coordinated operations for Lake Powell and Lake Mead on the Colorado River (Lower Colorado River Guidelines, Reclamation, 2007).

[4] A year is said to be in a “wet” state if its annual flow is equal to or greater than a threshold flow, often the mean or median flow. A year is said to be in a “dry” state if its annual flow is less than the threshold flow.

Prairie et al. (2008) used the information in the tree-ring chronologies to construct a stochastic model of annual sequences that was in turn used to construct traces of streamflows to be used as model input. A stochastic model is one that is driven by probabilities, and in this case, the probability of a particular year being used in a particular position in a sequence is based on information contained in the prehistoric tree ring record.

The flow reconstructions on which Prairie et al. (2008) and CRWAS are based were developed by Meko et al. (2007) and extend back to A.D. 762. The correlation between streamflow and tree growth (indicated by the width of an annual tree ring) is not perfect, so the annual sequence of prehistoric flows cannot be known exactly. As reconstructions go back in time there are fewer and fewer remaining tree-ring records with which to create a reconstruction, so the uncertainty in estimating the true value of the flow increases. In Meko et al., the uncertainty in estimating flow ranged from plus or minus 14 percent for the most recent model (using the largest number of records) to plus or minus 19 percent for the oldest model (using the smallest number of records). What is important for CRWAS is the ability of the tree rings to reconstruct whether a year was wet or dry, and the best model did that 83 percent of the time during the overlap period. If we remove the cases where either the reconstructed or observed flow was within 5 percent of the mean (that is, very close to changing from wet to dry or vice versa) the reconstruction got 98 percent of the cases correct. Information is not available to test the method for the earlier models.

This type of re-sequencing approach does not model the individual flow magnitudes, but instead arranges years from the observation period in sequences that are statistically consistent with the information about hydrologic conditions (i.e. wet or dry year) contained in the tree-ring chronologies. In the first application of this approach, for the Lower Colorado River Guidelines, sequences of annual flows at Lees Ferry were developed and subsequently disaggregated for use in the CRSS model. However, traces of any type of input data that is associated with an historical year, including complex, structured data, can be constructed using this approach. This allows a trace of monthly model input data to be constructed by re-sequencing the historical monthly input data one year at a time (including all monthly inflow data for all inflow points in a model) according to the order of years in a sequence.

For example, when building a trace of inflow data for the CDSS models, if a sequence contains the year 1964, the monthly model input data for all 227 natural flow points for 1964 would be appended to the input data set. This flexibility also allows the method to be used to extend climate-adjusted streamflows, historical and climate-adjusted weather, and historical and climate adjusted water use, so long as those data can be associated with an historical year.

Where to find more detailed information:

The details of the re-sequencing method, a technical description of the process and references to the relevant literature is provided in CRWAS Technical Memorandum Task 6.4 – *Methods for Alternate Hydrology and Water Use* available at http://cwcb.state.co.us/.

Table 2-3 and Figure 2-7 illustrate the results of re-sequencing. Table 2-3 shows 15-year portions of the historical sequence (1950-1964) and five sequences of years generated by the stochastic model used to extend historical hydrology. (For readability, only 15-years of each 56-year sequence are shown.) Note in Table 2-3 that years are sometimes used more than once in a single sequence and can sometimes follow in sequence, e.g. 2004 is used in positions 12 and 13 in Sequence 2.

Table 2-3 – Year Sequences

Sequence Position	Historical Record	Sequence 1	Sequence 2	Sequence 3	Sequence 4	Sequence 5
1	1950	1955	1992	1971	1976	1993
2	1951	1965	1955	1979	1954	1963
3	1952	1980	1956	1963	1957	1977
4	1953	1994	2003	1977	1998	2001
5	1954	1965	1995	1973	1983	1977
6	1955	1983	1994	1983	1994	1955
7	1956	1984	2004	1985	1961	1956
8	1957	1971	1960	2000	1991	1968
9	1958	1994	1995	1969	1992	1995
10	1959	1954	1994	1997	1962	1996
11	1960	1956	2001	1976	1972	1972
12	1961	1977	2004	1977	1993	1952
13	1962	2003	2004	1964	1996	1953
14	1963	2004	1991	2002	1997	2001
15	1964	1961	1992	1978	1953	1991

Figure 2-7 shows the year sequences in Table 2-3 converted into flow traces by replacing the historical year designation with the magnitude of flow from that historical year. The Historical Trace is the historical record of natural flows (in this case, at Lees Ferry Arizona on the Colorado River). The five traces from the extended historical hydrology all contain only annual flows from the Historical Trace. Figure 2-7 shows the entire 56-year period for each trace.

Trace	Historical Trace	Trace 1	Trace 2	Trace 3	Trace 4	Trace 5
Mean Flow	**14.26**	**15.62**	**14.56**	**13.01**	**16.02**	**13.16**

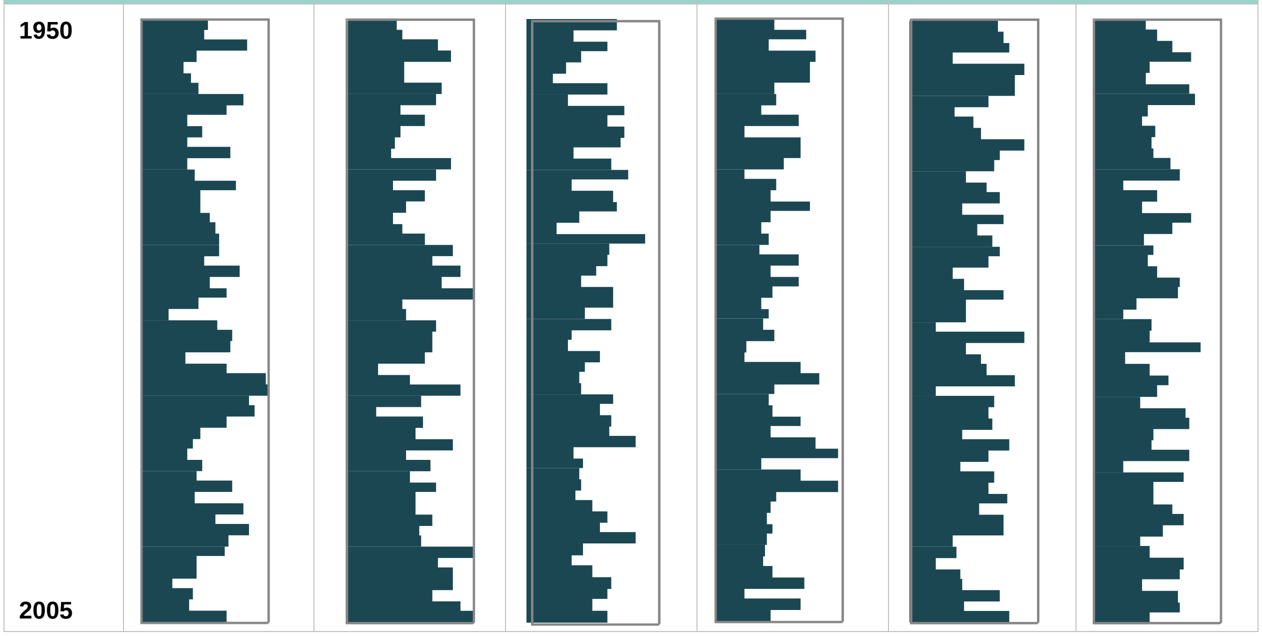


Figure 2-7 – Flow Traces

Figure 2-7 shows the mean flow over each 56-year trace just above the graphic representation of the trace. Mean flows vary significantly depending on the relative number of wet and dry years in the year sequence. If all of the years in the historical record were to be used in a trace, the mean of the trace will always equal the mean of the historical record regardless of the order in which the years/flows occur. Why the means differ from trace to trace is explained by examining the extent to which years recur or are omitted in the sequences shown in Table 2-3.

The value of using information from the paleo-record is that it describes droughts and wet spells that are more intense and of longer duration than those in the historical record. Trace 3 has a mean flow over the entire 56-year period that is more than one million acre-feet lower than experienced from 1950 through 2005. Trace 3 also has more severe dry periods than does the historical period: The driest ten-year period in the historical record is about 12.4 MAF while the driest ten-year period in Trace three is 10.8 MAF. Trace 3 contains three independent ten-year periods that are nearly one million acre-feet drier than the driest ten-year period in the historical trace.

Figure 2-7 shows only annual flow magnitudes, but the re-sequencing method as applied in the Study is used to assemble time-series of complex model input. For example, a trace of model input data for StateMod would be constructed from Sequence 1 by starting the trace with the entire CDSS data set (for 227 inflow points) for the year 1955. The trace would be extended to the second year by adding the entire data set for 1965, followed by the data for 1980, and so on until a full 56-year trace had been constructed.

Statistical Analysis of Extended Historical Hydrology

As described above, the process of developing the extended historical hydrology involved the generation of an ensemble of 100 hydrologic traces. No single trace will actually occur, just as the historical record will never be repeated exactly, but, collectively, the statistics of wet and dry spells in the ensemble of traces will provide information about the likelihood of future spells. Therefore, statistical analyses of the frequency of wet and dry spells were conducted on the ensemble of hydrologic traces. While the methods used to develop statistics for the alternate hydrology of climate change were described in CRWAS Technical Memorandum 7.12, the results were discussed only in qualitative terms. During the outreach process following publication of the draft CRWAS Phase I Report, stakeholders requested that the final CRWAS Phase I Report provide more information on drought and surplus spells. Meanwhile, the statistics of spells calculated in CRWAS Tasks 6.7 and 7.12 for four sites were reported in the Colorado Drought Mitigation and Response Plan (Drought Mitigation Plan, CWCB, 2010), which included discussion (Annex C) on the implications of climate change for drought (note that the Drought Mitigation Plan covers the entire state, but the CRWAS only quantified the impact of projected climate on spell statistics for the Colorado River Basin. Subsequently, as part of refinements to the Drought Mitigation Plan, an effort was made to develop more meaningful statistical measures of spell frequency and intensity and to develop better ways of communicating those measures. These efforts were continued as part of the refinement of the CRWAS.

For water supply planning, the length of wet and dry periods (or spells) is especially important. For example, several consecutive wet years followed by several dry years are much worse in terms of required reservoir storage than a series of alternating wet and dry years if even if the average flows for the two cases are identical. For the purposes of this Study, spells are defined as continuous sequences of two or more years of the same category (i.e. dry or wet), regardless of when they occur, i.e. every spell is counted even if it is “nested” inside a longer spell (Tarawneh and Salas, 2009). Several statistics are used to characterize spells in CRWAS. The *threshold* is the flow used to characterize years—if total volume of flow in a year is less than the threshold, the year is categorized as a dry year; otherwise, the year is categorized as a wet year (in the unlikely event that an annual flow is exactly equal to the threshold that year will be classified as a wet year). The *duration* of a spell is the number of continuous years of the same category (wet or dry). The *magnitude* of a spell is the cumulative amount by which the total volume over the duration of the spell varies from the threshold volume (the threshold flow times the duration of the spell). A wet spell produces a *surplus* while a dry spell produces a *deficit*. The *intensity* of a spell is the amount that the average flow during the spell differs from the threshold. Wet spells produce positive intensities while dry spells produce negative intensities. The *frequency* of a spell is a measure of how often it is expected to occur. Frequency is often stated as a *return interval*; a “100-year drought” is a dry spell that is expected to recur (return) once a century. Frequency is also expressed as a probability; there is a one-percent probability that a 100-year drought will begin in any given year. Spell frequency is most often specified for particular spell durations. Less often frequency is expressed for a particular spell magnitude or intensity and some research estimates the frequency of combinations of duration and intensity, but this is rare in practice.

The spell statistics originally developed for CRWAS and reported in the Drought Mitigation Plan were based on the conventional hydrologic practice where the threshold is set as the mean of flows in the trace. Using this convention for climate-adjusted flows assumes a point of view at some time in the future when climate change has stabilized and society has adopted the changed conditions as the norm. At that hypothetical time in the future, the spells would be superimposed on a new mean flow that has become "normal." Using the original approach, spell statistics for projected climate cases are similar to the corresponding statistics for the alternate historical hydrology, because using the future mean flow as the threshold effectively removes the climate impact on mean flows. Statistics calculated this way are not focused on answering the central question: How much will spells change relative to the conditions of the historical observed record, which current policies and systems have been designed to handle? This question is most precisely answered through detailed water resources modeling, but an indication of the answer can be obtained by calculating the characteristics of spells for projected flows based on the historical mean rather than the mean of each individual climate scenario.

The original CRWAS analyses examined the frequency of the longest spell in each 56-year trace in the alternate historical hydrology (AHH). A new approach was adopted for this revision that looked at the entire AHH to determine the frequency of a spell as long as the *historic spell,* the longest spell in the historical record. This approach answers the question: What is the likelihood that a spell of a particular length will begin next year? The refined method calculates the return interval and the intensity of a dry or wet spell that has the same length as the longest spell experienced during the historical period.

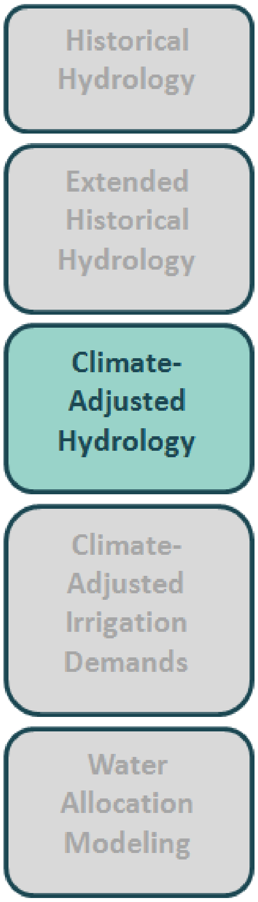
Drought statistics expressed in terms of non-exceedance values, as was done with the results of the original CRWAS analysis, may be difficult to relate to experience because a small change in the non-exceedance value for a rare event can substantially affect risk. For example, the return interval of an event with a 98 percent non-exceedance frequency is 50 years while the return interval for an event with a 96 percent non-exceedance frequency is 25 years; what at first glance appears to be a two percent change actually represents a doubling of frequency. Further, presenting the length and severity of droughts as probabilities or in terms of frequency, which is often confused with probability, may introduce confusion with the unknown probabilities of the climate cases. For these reasons, another approach was developed to express spell occurrence in terms of return intervals.

The refined method calculates the return interval and the intensity of a dry or wet spell that has the same length as the longest spell experienced during the historical period. Spell statistics are calculated for the alternate historical hydrology and for the ten projected climate cases. The results of these analyses are presented in Section 3.3 and Appendix C.

Where to find more detailed information:

For more detail on the calculation of spell statistics see CRWAS Task 6.7 – *Summarize Alternate Historical Hydrology* and CRWAS I(b) Task 5-2: *Spell Statistics (refinement to CRWAS Phase I Tasks 6.7)* technical memoranda available at http://cwcb.state.co.us/.

2.3.4 *Climate-Adjusted Hydrology*



Coordination with JFRCCVS and CCTAG

A second study of climate change impacts, the Joint Front Range Climate Change Vulnerability Study (JFRCCVS) proceeded contemporarily with the CRWAS. The JFRCCVS is a cooperative effort among six front-range water providers and the CWCB. The CWCB directed that the CRWAS coordinate its efforts with the JFRCCVS to help assure that the two studies are as cost effective as possible, to maximize consistency and comparability of results (while remaining consistent with the different objectives of each study) and to maximize the technical value of the two studies to their respective stakeholders. In addition, the CWCB directed that the CRWAS would review the Study approach and results with the Colorado CCTAG. The most important elements of these coordination activities involved a review of the proposed CRWAS technical approach that occurred before the Study Scope of Work was finalized, selection of the time frames at which future climate would be characterized, and selection of the climate projections to be used to characterize the future time frames.

For the first step in coordination between the CRWAS and the JFRCCVS, prior to the development of the detailed technical scope of work for the CRWAS, an outline of the technical approach suggested by CRWAS for use in characterizing climate-adjusted hydrology was provided to the JFRCCVS and the CCTAG. A joint meeting of members of the CRWAS technical team, the JFRCCVS technical team and stakeholders, and the CCTAG was held to address the technical validity of the approach being considered by CRWAS and its consistency with the approach being considered by the JFRCCVS. The joint review identified areas in both the CRWAS and JFRCCVS study approaches where refinements would provide benefits in terms of technical reliability and consistency between the two studies.

The most significant coordination between the JFRCCVS and the CRWAS involved selection of time frames at which future climate would be characterized and selection of the climate projections to be used to characterize the future time frames. At the time that the CRWAS began its efforts to develop its approach, the JFRCCVS had already identified two time frames for characterization of future climate, 2040 and 2070, to be characterized by average conditions over the periods 2025-2054 and 2055-2084, respectively. Initially, the JFRCCVS study considered the time frames used by the Boulder Climate Change Study (2030 and 2070; Smith, et al., 2009). The JFRCCVS technical team felt that 2030 was too early to see significant development of climate change impacts, so 2040 was used as the early time frame for the JFRCCVS. These two time frames were acceptable to the CCTAG, and were therefore adopted by the CRWAS.

The CRWAS used a historical period from 1950 through 2005, which extends six years longer than the period used by JFRCCVS. At the time JFRCCVS began, the gridded weather data used by both studies (see section 2.3.4) had not been extended beyond 1999. The CRWAS study team used the extended data to include the drought beginning in 2000.

Where to find more detailed information:

Coordination between the JFRCCVS and CRWAS continued during the course of the two studies; details of those coordination activities are described in CRWAS Technical Memorandum Task 7.1 – *Coordination with Front Range Vulnerability Study*, available at http://cwcb.state.co.us/.

Selection of Downscaled Climate Projections

A climate *projection* is the output of one run of a GCM using a specific set of initial and boundary conditions and a specific set of input data. Climate projections are used in CRWAS to characterize possible future precipitation and temperature conditions, which in turn affect natural flows and water use. For practical purposes, the climate projections available to JFRCCVS and CRWAS were those in an archive created and maintained by a joint effort of the Lawrence Livermore National Laboratory (LLNL), the Bureau of Reclamation, and Santa Clara University (SCU) (LLNL-Reclamation-SCU archive). The LLNL-Reclamation-SCU archive contains 112 projections created using 16 different climate models and three different emission scenarios.

Where to find more detailed information:

The CWCB asked the Western Water Assessment to develop a report that synthesized information about climate change that was relevant to Colorado. That report, *Climate Change in Colorado, A Synthesis to Support Water Resources Management and Adaptation* (Ray et al., 2008), provides a great deal of valuable information about Colorado's climate, climate science, and projected climate conditions in Colorado. It provides particularly valuable descriptions of greenhouse gas emission scenarios and global climate models (http://cwcb.state.co.us/).

Climate Models (GCMs)

A GCM is a mathematical model of the Earth's atmosphere and its interaction with the ocean and land surface. Global climate models are used for weather forecasting and projecting climate change. In the latter application, they provide estimates of future conditions that reflect the levels of greenhouse gas emissions. GCMs divide the atmosphere and the ocean along lines of latitude and longitude and into horizontal layers, to form a three-dimensional grid. In the CRWAS study area, grid cells average about 200 miles on a side. More detailed climate models, referred to as Regional Climate Models (RCMs) may provide better resolution of regional precipitation patterns. Even more finely detailed models may someday be able to resolve orographic effects of Colorado's mountainous terrain. However, these more detailed approaches still rely on GCMs to define boundary conditions and are therefore subject to many of the biases and uncertainties inherent in the GCMs (Harding, et al., 2012). There are not a sufficient number of runs of RCMs available to characterize the range of projections of future climate in the study area, which was one of the goals of CRWAS. In the future, modeling centers may develop large ensembles of RCM outputs that would characterize uncertainty, but at the time of this work relying on GCM output was the only practical approach that allowed the use of a broad ensemble of model outputs.

Emission Scenarios

Projections of future changes in climate attributed to human activity rely on projections of future concentrations of greenhouse gases (GHG), which in turn depend on current concentrations and future rates of GHG emissions. GHG emissions depend, in complex ways, on socio-economic development, technology, demographics and politics. The Intergovernmental Panel on Climate Change (IPCC) has developed a number of "storylines" of future global conditions, which are used as the basis for estimates of future GHG emissions. These storylines are documented in the Special Report on Emissions Scenarios (SRES) and are often referred to as SRES scenarios. IPCC did not assign a likelihood to the SRES scenarios—each is considered one "alternative image[s] of how the future might unfold" (Nakicenovic et al., 2000, Technical Summary). While different emissions scenarios may impact different regions of the globe to varying degrees, emissions scenarios are global in nature and do not have a specific linkage to a region. From the four SRES scenario "families" (A1, A2, B1, B2), only the B1, A1B (a member of the A1 family) and A2 scenarios have been used as the basis for projections on many GCMs. These have come to be known, respectively, as the "low", "medium" and "high" emissions scenarios, based on their impact on climate conditions in the year 2100[5].

Downscaling

GCM output is available in grid scales that range from about 100 to about 200 miles square (10,000 to 40,000 square miles) a substantial portion of the area of western Colorado. While one GCM grid cell covers from 10,000 to 40,000 square miles, a substantial mountain watershed might cover several hundred to a thousand square miles, and many tributaries drain considerably smaller areas. Before GCM output can be used for analysis of local conditions, or for local hydrologic modeling, it must go through a process called downscaling, which relates the large scale GCM data to detailed terrain and observed climate conditions. Downscaling represents processes that occur at a smaller, local scale and over shorter time frames than can be simulated by a GCM (Barsugli et al., 2009). GCM projections contain bias, which is exhibited as systematic error in replicating observed conditions, and these biases are usually reduced during downscaling in a process called bias correction. The bias-correction process serves as an ex post calibration process to adjust the projected climate results by the amounts necessary to reduce the bias in simulations of historical climate.

Downscaling techniques fall into two principal categories, statistical downscaling and dynamical downscaling. Statistical downscaling uses a statistical model to relate large-scale GCM data to local, short term conditions. This is similar in concept to the use of a regional regression to estimate ungaged flows. Dynamical downscaling uses a smaller scale regional climate model (RCM) "nested" within a larger-scale GCM. The RCM operates on a finer grid than the GCM and simulates a small portion of the earth (hence, the terms "regional" versus "global"). Because it simulates conditions on a smaller spatial scale, the RCM must also use a shorter time step. The conditions at the edges of the RCM grid are updated by the GCM at its longer time step and the RCM then proceeds to simulate conditions at its smaller spatial and temporal scale.

Both statistical and dynamical downscaling techniques (using RCMs) rely on the representation of climate conditions provided by the GCM and both approaches have been used for impact studies. However, because RCMs are expensive to run, only a small subset of the available

[5] The impacts of different GHG emissions scenarios do not begin to diverge substantially until roughly 2050.

GCM runs have been downscaled for a particular region. Thus, RCMs cannot reflect the full range of possible future climate conditions that have been generated by the GCMs. Because a principal objective of CRWAS and JFRCCVS was to represent the uncertainty inherent in GCM projections, both studies elected to use statistically downscaled projections.

JFRCCVS and CRWAS used statistically downscaled and bias-corrected data developed jointly by the Bureau of Reclamation, Santa Clara College and the Lawrence Livermore National Laboratory (LLNL-Reclamation-SCU archive) (Maurer et al., 2007; WCRP CMIP3, 2008). These data have been placed in a readily available archive that contains downscaled output for 112 projections of future climate based on 16 GCMs and the B1, A1B and A2 emission scenarios. The LLNL-Reclamation-SCU archive has been developed using peer reviewed methods (Maurer et al., 2002) and is currently being used by the Bureau of Reclamation for climate change impact analyses. The data are aligned spatially to match the NOAA/NASA Land Data Assimilation System (LDAS; Mitchell et al., 2004) grid, which has a spatial resolution of 1/8th degree latitude by longitude, (the size of a USGS Quadrangle map.)

The downscaled data obtained from the LLNL-Reclamation-SCU archive includes the effect of topography and the variability of local weather on a monthly time step. The approach used in the Study to adjust observed weather, described below, incorporates the variability associated with the daily pattern of weather observed in the mountainous terrain of the study area.

The North American Monsoon (NAM) is an important source of moisture during many summers in Colorado. Many existing GCMs do not reliably represent the regional scale atmospheric circulation that drives the NAM and there is no consensus regarding future changes in monsoonal precipitation in the region (Karl, et al., 2009, Liang, et al., 2008, Lin et al., 2008). The monsoon may intensify or it may weaken, and its spatial extent may change, but this is difficult to determine from the existing global climate models. This is a recognized uncertainty in the current evolving state of global climate models. As models with finer resolution are developed, more reliable projections of precipitation from the monsoon should become available. The downscaling process, and the approach adopted by CRWAS to adjust historical climate both serve to incorporate the historical extent of the precipitation arising from the monsoon.

Where to find more detailed information:

For more information on climate models and downscaling see *Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change,* published by the Water Utility Climate Alliance (WUCA) (http://www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf)

Selection of Projections

GCMs differ in their simulation approach and their degree of sophistication, and different runs (projections) of a particular GCM using the same SRES scenario may differ in how they are initialized. No two projections will be the same, and there can be substantial differences among multiple projections from the same GCM and based on the same SRES scenario.

As noted above, one objective for the Study was to maintain consistency with the JFRCCVS, so CRWAS first used the same projections selected by JFRCCVS. After consultation between the JFRCCVS and CRWAS technical teams, JFRCCVS adopted an approach for selection of projections that is described below. After analysis of the projected impacts of the selected projections, the CRWAS study team determined that the five projections selected for 2070 did not incorporate the selected goal for the range of future conditions for the CRWAS study area and replaced the original 2070 projections with five newly-selected projections, as described in subsequent sections.

For CRWAS and the Front Range Study the time frames for impact assessments were established at 2040 and 2070. Each time frame was characterized by average conditions over a 30-year period (2025-2054 and 2055-2084, respectively). For each of those time frames, five climate projections were selected from a set of 112 readily-available downscaled projections as described in CRWAS Technical Memorandum Task 7.2: *Climate Change Literature Review and Methods Evaluation* and in Woodbury, et al. (2011). To help account for potential outliers in the projections, the CRWAS and the JFRCCVS, in consultation with the CCTAG, selected climate projections based only on their simulated change in temperature and precipitation, with the objective of representing approximately 80 percent of the range of conditions reflected across all of the readily available projections. Other attributes of individual projections were not used in this selection. Currently, there is not sufficient scientific information to evaluate the suitability of individual model codes or individual model runs for projecting conditions in the Colorado River Basin. Projections were not selected based on emissions scenario because the objective of the selection was to represent the total uncertainty associated with projections of future climate, including the uncertainty associated with estimates of future emissions. Climate models differ significantly one from another, but the effect of different emission scenarios is much smaller, even at the end of the century (Willby & Harris, 2006; Harding, et al., 2012).

Because the hydrologic impacts attributable to a projection could not be known without hydrologic modeling, projections were selected based on five qualitative future climate scenarios defined as follows:

- Hot and Dry
- Hot and Wet
- Warm and Dry
- Warm and Wet
- Median

For each future time frame, a projection was selected for each of the five qualitative scenarios. The selected projections were intended to cover 80 percent of the overall range of climate change represented by the entire set of 112 projections. For each of the five qualitative scenarios, a characteristic value of change in temperature and precipitation was determined as shown in Table 2-4.

Table 2-4 – Characteristic Temperature and Precipitation for Qualitative Future Climate Scenarios

Qualitative Scenario	*Characteristic Temperature*	*Characteristic Precipitation*
Hot and Dry	90th Percentile[6]	10th Percentile
Hot and Wet	70th Percentile	70th Percentile
Warm and Dry	30th Percentile	30th Percentile
Warm and Wet	10th Percentile	90th Percentile
Median	50th Percentile	50th Percentile

Figure 2-8 illustrates the characteristic conditions for the qualitative scenarios in the context of all 112 projections of future temperature and precipitation. Each projection is designated as a cross, the characteristic conditions for the five qualitative scenarios are designated by the filled circles and the selected projections are designated by filled triangles. Each projection or characteristic condition is plotted at its average change in temperature and precipitation. Average conditions for the 2040 time frame are calculated over the period 2025 through 2054 and for the 2070 time frame are calculated over the period 2055 through 2084.

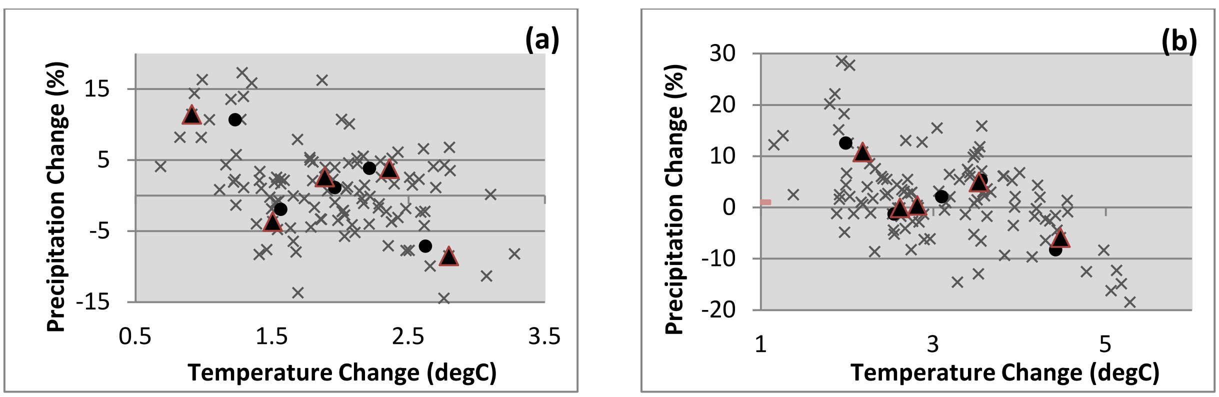


Figure 2-8 – Annual Temperature and Precipitation Changes for 112 individual GCMs[7]

[6] *Percentile* is the same as *relative position*, and both terms refer to the position of a particular measurement, such as a temperature or an amount of precipitation, in a sorted list that contains all values of that measurement. Typically, percentiles and relative position are expressed relative to the smallest value, so the 90th percentile is the value that is 90 percent of the way from the smallest value to the largest value, in terms of the number of values. For example, if there are about 100 values, the 90th value counting from smallest to largest would be at about the 90th percentile (but not exactly at the 90th percentile because adjustments are usually made when calculating percentiles to insure that no value will be at exactly 0 percent or 100 percent).

[7] Idealized Qualitative Scenarios as compared to 1950-1999 annual averages (Woodbury, et al., 2010) (a) 2040 projections; (b) 2070 projections; projections are designated by a cross; offset scenarios are designated by a filled circle; selected projections are designated by a filled triangle.

For each of the two time frames, five projections were selected based on their proximity to the characteristic values for the five scenario points and based on how similar their monthly pattern precipitation change is to other projections near the characteristic values. The selected projections are shown in Table 2-5.

Table 2-5 – Original Selected Projections

Qualitative Scenario	*Time Frame*	*SRES Scenario*	*Model*	*Version*	*Run*
Warm & Wet	2040	A2	ncar_pcm	1	3
Warm & Dry	2040	A2	mri_cgcm	2.3.2a	1
Median	2040	B1	cccma_cgcm	3.1	2
Hot & Wet	2040	A1B	ncar_ccsm	3.0	2
Hot & Dry	2040	A2	miroc	3.2.medres	1
Warm & Wet	2070	A2	ncar_pcm	1	3
Warm & Dry	2070	A1B	mri_cgcm	2.3.2a	4
Median	2070	B1	mpi_echam	5	1
Hot & Wet	2070	A1B	ncar_ccsm	3.0	2
Hot & Dry	2070	A1B	gfdl_cm	2.0	1

Analysis of Selected Projections

At the time projections were selected, the CRWAS and JFRCCVS technical teams did not have information with which to evaluate how well the selected projections met the objective of representing 80 percent of the range of impacts across all of the 112 available projections. After the CRWAS hydrologic modeling and water resources modeling had been completed, the Bureau of Reclamation began simulating the impact of projected climate on natural flows in the Colorado River Basin as part of the Colorado River Basin Water Supply and Demand Study (Bureau of Reclamation, 2011). As part of that work, Reclamation developed projected natural flows for 29 points in the Colorado River Basin for all of the available 112 downscaled projections using a Variable Infiltration Capacity (VIC) model that is very similar to the model used in CRWAS. Development of these projected natural flows is described in Bureau of Reclamation (2010) and Harding et al. (2012).

Comparison of the selected projections with the full set of projections revealed biases in the sets of selected projections. The bias in the set of 2040 projections was judged to be small enough that it would not interfere with assessment of impacts for that time frame, but the bias in the set of 2070 projections was much larger and was judged to introduce an unacceptable bias in the assessment of hydrologic conditions at that time frame. Accordingly, the projections for 2040 were used as the principal basis for results presented in body of the Draft Phase I CRWAS Report while results based on 2070 projections were provided in the Appendices.

The selected projections were evaluated using an index flow that was heavily weighted toward the water-producing regions of the Colorado River Basin within Colorado[8]. The watersheds

[8] The selected projections were originally evaluated at the Colorado River near Glenwood Springs, because that watershed was more representative of the smaller area used by the Front Range Study for selecting projections. The results of that evaluation were presented in the Draft Phase I CRWAS Report.

depicted in Figure 2-9 were selected as the basis for the index flow because they drain a substantial portion of the Colorado River Basin within Colorado and do not drain significant areas of more arid lands outside the State. Flows arising from that portion of the San Juan River between Archuleta, New Mexico and Bluff, Utah were not included in the index flow because simulated projected flows for the San Juan Basin are available only at those two locations, and the basin above Bluff and below Archuleta includes a large area of very arid lands outside the State of Colorado. Flows at these twelve points were summed to create an index flow that is intended to be representative of the natural water supply within the State. The Colorado River at Glenwood Springs is station 1 in Figure 2-9.

Some comments received on the Report suggested that the selected projections be evaluated at Lees Ferry rather than Glenwood Springs. Because the watershed above Lees Ferry contains large areas of arid lands outside the because the focus of CRWAS is weighted toward water availability within the State of Colorado, the study team elected to use the index flow.

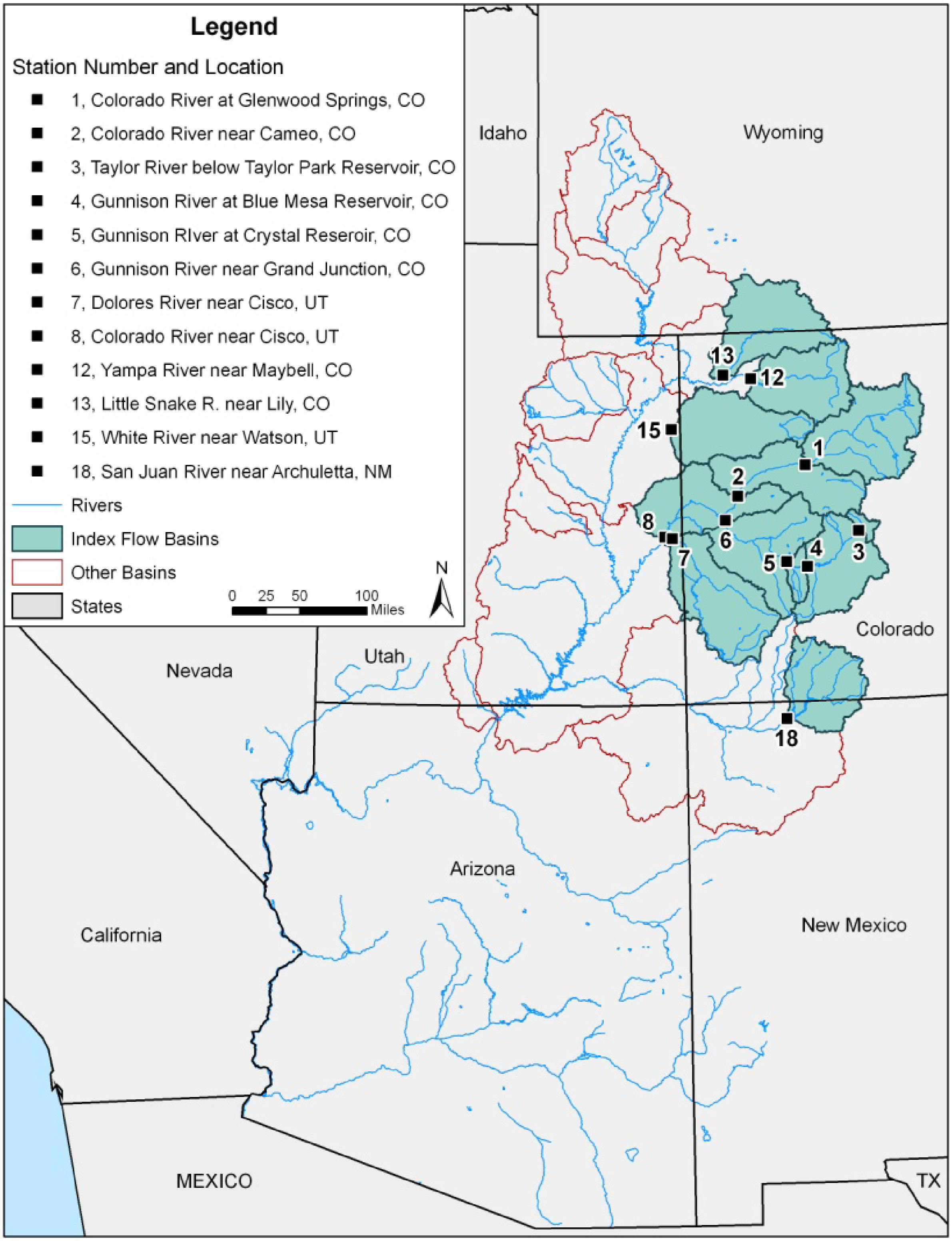


Figure 2-9 – Selected CRSS Index Flow Watersheds.

Table 2-6 summarizes the attributes of the original selected climate projections. Figure 2-10 shows the original selected projections in the context of the cumulative distribution of flow change (expressed as a percentage) for both time frames at the index flow.

Table 2-6 –Attributes of Selected Climate Projections

	Index Flow	
	2040	**2070**
Maximum relative position	92%	77%
Minimum relative position	15%	19%
Range of relative position	77%	58%
Mean flow change of all projections	-5%	-7%
Mean flow change of selected projections	-4%	-12%

In Table 2-6, flow change is the percent change in the average annual index flow that results from hydrologic modeling of the projection. The relative position is the same as is described for Figure 2-10. The relative position of each projection is expressed as a percent of the distance from the lowest flow change to the highest flow change.

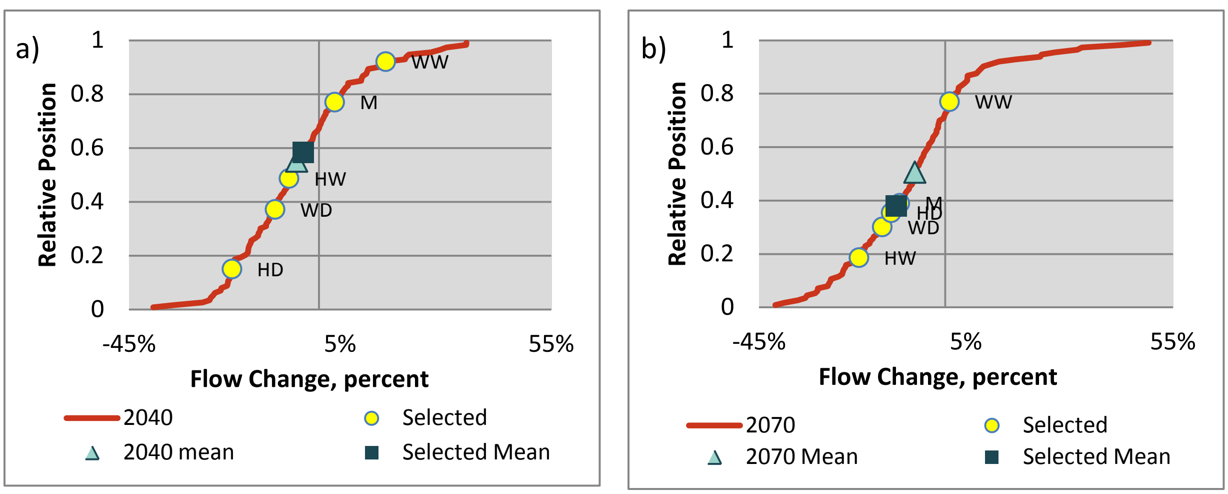


Figure 2-10 – Relative position of selected projections in cumulative distribution function of all 112 climate projections[9]

Figure 2-10 is a *cumulative distribution function*, which is simply a plot of the relative position of all the projections, sorted from smallest to largest, against the projected change in natural flow. The projection with the largest decrease (the largest decrease is the most negative number and thus the smallest number) and is at the lower/left end of the curve. The projection with the largest increase in flow is at the highest/right end of the curve. Magnitudes of change in flow are plotted along the horizontal axis.

[9] from the downscaled archive.a) 2040, b) 2070; solid red line represents the empirical cumulative distribution function of the flow change for all of the 112 projections; yellow circles represent the relative positions of the five selected projections; the light blue triangle represents the mean flow change for all 112 projections and the dark blue square represents the mean flow change for the selected projections. HD is Hot and Dry; HW is Hot and Wet; WD is Warm and Dry; WW is Warm and Wet and M is Median

Figure 2-10 and Table 2-6 show that the initial approach used to select projections in CRWAS and the Front Range Study did not meet the objective of representing 80 percent of the projection-to-projection variability for either time frame. The 2040 projections represent 77 percent of the range of all anomalies for the index flow, while the corresponding value for the 2070 projections is 58 percent. The mean flow change for the 2070 projections for the index flow showed a significant dry bias relative to the mean flow change for all projections. The selected projections in Figure 2-10 are labeled according to the qualitative climate scenario that they represent (HD is Hot and Dry; HW is Hot and Wet; WD is Warm and Dry; WW is Warm and Wet and M is Median). It is apparent from Figure 2-10 that the relative impact of the qualitative climate scenarios changes from 2040 to 2070, e.g. the Hot and Dry scenario was the driest scenario in 2040 but is the third driest in 2070. The unexpected results evident in Figure 2-10 illustrate the difficulty in estimating hydrologic impact based on temperature and precipitation alone. In order to improve the representation of 2070 conditions, a new set of projections for 2070 were selected by matching the plotting position of the 2040 projections for the index flow. The selected projections are shown in Table 2-7 and Figure 2-11, and the attributes of the two sets of projections are summarized in Table 2-8.

Table 2-7 – New Selected Climate Projections

Time Frame	SRES Scenario	GCM	Run	Flow Change	Relative Position
2070	a2	ncar_ccsm3_0	4	-24.1%	15.0%
2070	a1b	mpi_echam5	3	-13.0%	37.2%
2070	a2	mpi_echam5	1	-7.8%	48.7%
2070	a2	ncar_pcm1	3	1.0%	77.0%
2070	a2	cccma_cgcm3_1	2	13.0%	92.0%

Table 2-8 – Attributes of New Selected Climate Projections

	Index Flow	
	2040	**2070**
Maximum relative position	0.92	0.92
Minimum relative position	0.15	0.15
Range of relative position	0.77	0.77
Mean flow change for all projections	-0.05	-0.07
Mean flow change for selected projections	-0.04	-0.06

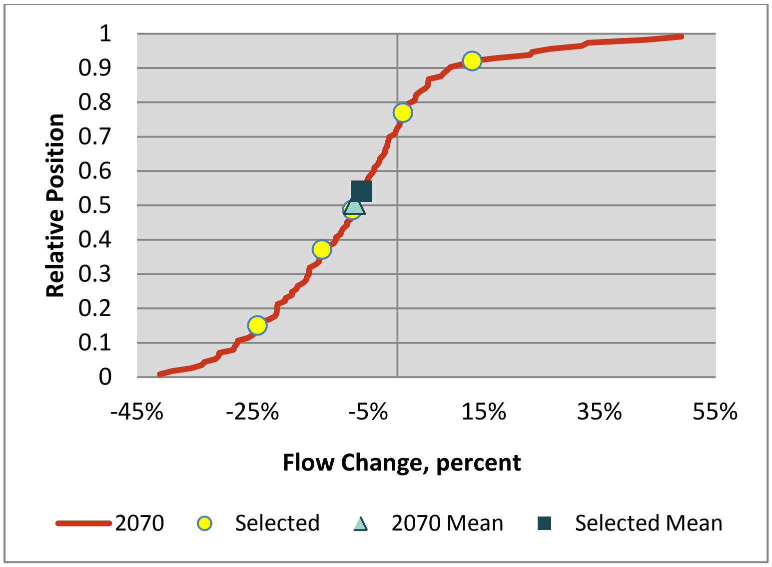


Figure 2-11 – Relative position of new selected projections for 2070[10]

When evaluated for the index flow representing a broad area of the Colorado River basin in Colorado, the new selected projections for 2070 cover the same 77 percent of the distribution of flow impacts as the 2040 projections and, as is the case for 2040, the mean flow impact for the new 2070 projections is one percent higher than the mean impact for all 112 projections. Table 2-9 shows the climate and streamflow impacts of the ten projections selected to represent 2040 and 2070.

Table 2-9 – Selected Climate Projections

SRES Scenario	GCM	Version	Run	Precipitation		Temperature		Flow	
				Change (%)	Relative Position	Change (°C)	Relative Position	Change (%)	Relative Position
2040 Selected Projections									
A2	miroc	3.2.medres	1	-8%	6%	2.9	95%	-21%	15%
A2	mri_cgcm	2.3.2a	1	-3%	27%	1.5	27%	-10%	37%
A1B	ncar_ccsm	3	2	1%	54%	2.5	82%	-7%	49%
B1	cccma_cgcm	3.1	2	4%	73%	1.9	45%	4%	77%
A2	ncar_pcm	1	3	9%	91%	1.0	3%	16%	92%
2070 Selected Projections									
A2	ncar_ccsm	3.0	4	-4%	19%	4.5	92%	-24%	15%
A1B	mpi_echam	5	3	-1%	37%	3.6	67%	-13%	37%
A2	mpi_echam	5	1	1%	50%	3.7	70%	-8%	49%
A2	ncar_pcm	1	3	3%	69%	2.3	19%	1%	77%
A2	cccma_cgcm	3.1	2	11%	90%	3.7	69%	13%	92%

[10] Cumulative distribution function of change in natural flow for all 112 climate projections from the downscaled archive.

Designation of Projections

In the Draft CRWAS Phase I Report the selected projections were designated by their qualitative climate scenario, e.g. hot and wet. The analysis described above indicates that the qualitative scenarios cannot predict the range or ordering of projected impacts on natural flows. Further, the new 2070 projections were not selected according to the qualitative climate scenarios but instead were selected to have the same plotting position as the 2040 projections. The climate conditions in these projections will not be consistent with the qualitative scenarios for either the 2040 projections or the original 2070 projections, and in fact, most of the new 2070 projections do not fall near the characteristic conditions of qualitative scenarios, as shown in Figure 2-12. For these reasons, the projections are designated in this report as shown in Table 2-10.

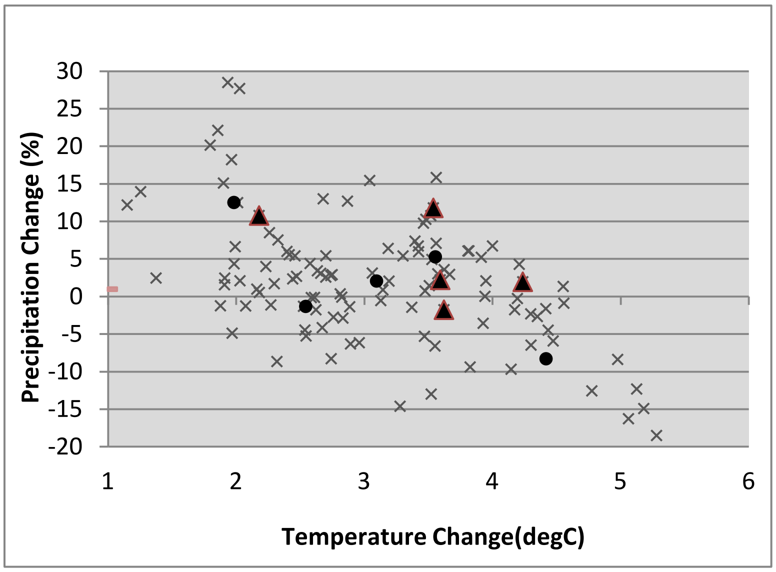


Figure 2-12 – Annual Temperature and Precipitation Changes for new 2070 projections

Table 2-10 – Attributes of New Selected Climate Projections

SRES Scenario	GCM	Version	Run	Designation
2040 Selected Projections				
A2	miroc	3.2.medres	1	2040-A
A2	mri_cgcm	2.3.2a	1	2040-B
A1B	ncar_ccsm	3	2	2040-C
B1	cccma_cgcm	3.1	2	2040-D
A2	ncar_pcm	1	3	2040-E
2070 Selected Projections				
A2	ncar_ccsm	3.0	4	2070-F
A1B	mpi_echam	5	3	2070-G
A2	mpi_echam	5	1	2070-H
A2	ncar_pcm	1	3	2070-I
A2	cccma_cgcm	3.1	2	2070-J

Where to find more detailed information:

For more descriptions of greenhouse gas emission scenarios and global climate models see *Climate Change in Colorado, A Synthesis to Support Water Resources Management and Adaptation* (Ray et al., 2008)*,*

For more information on climate models and downscaling see *Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change,* published by the Water Utility Climate Alliance (WUCA) (http://www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf)

For detailed information on emissions scenarios, see *IPCC Special Report on Emissions Scenarios: Summary for Policymakers (http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf).*

For more detailed information on the selection of new 2070 projections, see CRWAS Technical Memorandum Task CRWAS Phase I (b) – Task 3.1– *Projection Selection (refinement to CRWAS Phase I Tasks 7.1, 7.2 and 7.5)*, available at http://cwcb.state.co.us/.

Climate-Adjusted Weather

Climate change affects weather, which in turn affects streamflow and water use. *Climate-adjusted weather* is used in hydrology modeling (performed with the VIC model discussed below), to develop estimates of *climate-adjusted natural flows.* Climate-adjusted weather is also used in consumptive use models (see Section 2.3.5) to develop estimates of *climate-adjusted* CIR. Hydrology and water use modeling use weather data in different forms, but the approach to applying adjustments to reflect climate change is the same.

Historical Weather

CRWAS hydrology modeling uses daily weather data that have been disaggregated to a regular grid. The data set used in CRWAS, developed as described in Maurer, et al. (2002), is a model-derived dataset of daily maximum and minimum temperature, precipitation depth and wind for the conterminous United States and portions of Canada and Mexico spanning from 1950 through 2005. The grid geometry of this data set is identical to the climate projections from the LLNL-Reclamation-SCU archive described below.

The availability of the Maurer, et al. gridded weather to serve as the basis for the CRWAS hydrology modeling was the limiting factor in determining that the CRWAS historical hydrology period would run from 1950 through 2005.

CRWAS CIR estimates do not rely on the gridded weather but instead use observed temperature and precipitation data from 54 weather stations in the Study basins.

Applying Climate Adjustments

The first step, common to developing both climate-adjusted CIR and climate-adjusted natural flows, is generating a time series of weather that represents the climate-adjusted condition—the observed weather adjusted to represent the projected change in temperature and precipitation[11]. The development of the climate-adjusted weather is illustrated in Figure 2-13.

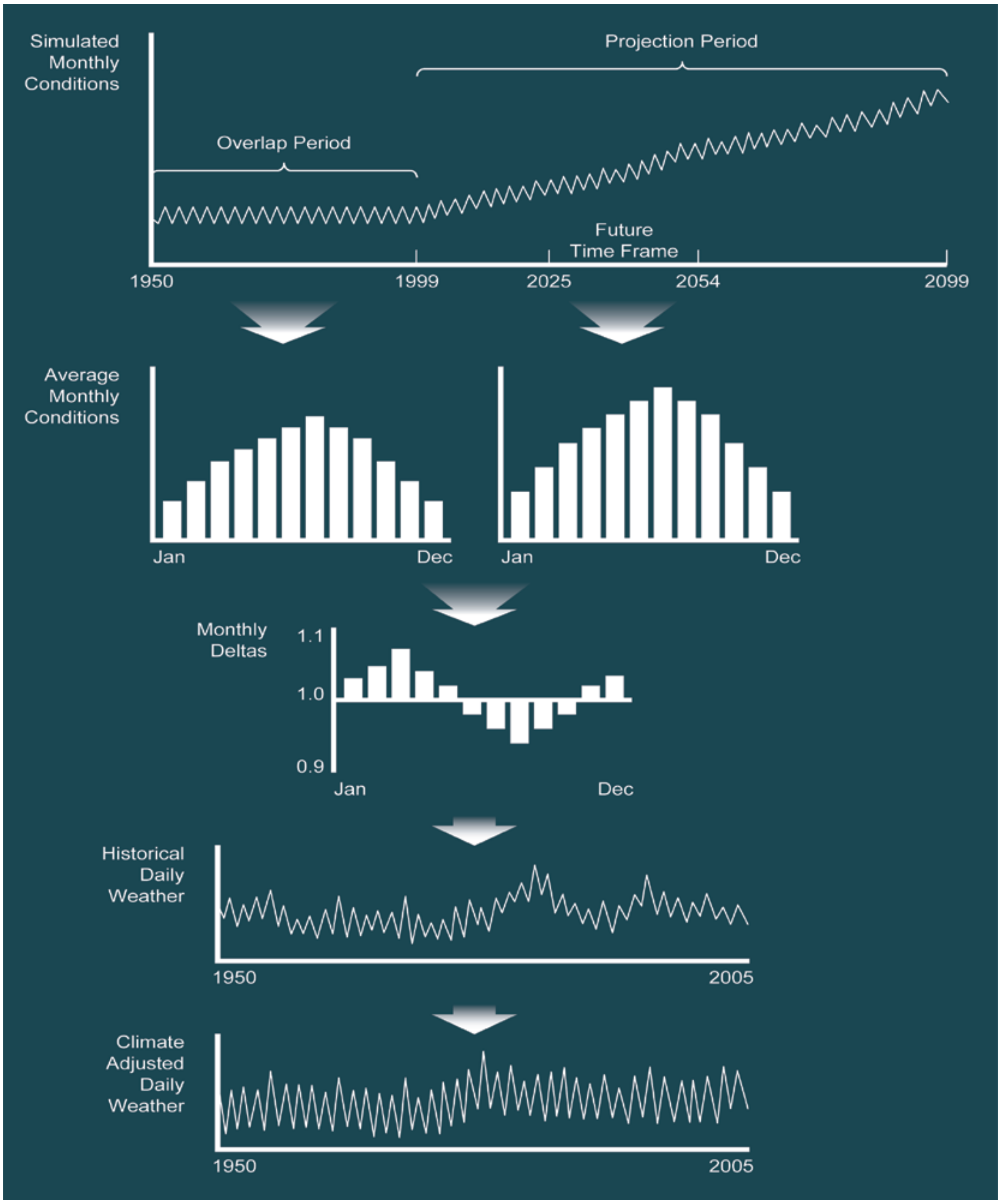


Figure 2-13 – Illustration of Development of Climate-Adjusted Weather

A climate projection is the output of one run of a global climate model (GCM) with a given set of initial and boundary conditions. The climate projection is illustrated in the Simulated Monthly Conditions graph of Figure 2-13. Each projection consists of an overlap period and a projection

[11] Although wind is an important factor in evapotranspiration, no down-scaled data for surface winds are available, so wind was not adjusted in the CRWAS climate-adjusted weather data set.

period. In the LLNL-Reclamation-SCU archive, the overlap period runs from 1950 through 1999 and the projection period runs from 2000 through 2099, as illustrated in the Simulated Monthly Conditions graph in Figure 2-13. Projected climate change at a particular point in the future is determined by comparing the average condition during all or part of the overlap period with the average future condition. In CRWAS, the change in precipitation representing conditions in the *future time frames* of 2040 and 2070 was characterized by calculating the monthly average precipitation for the period 2025 – 2054 and 2055 – 2084, respectively, and for the overlap period. (Only the 2040 time frame is illustrated in Figure 2-13. The results of these calculations are illustrated in the Average Monthly Conditions graphs in Figure 2-13. For each month of the year the projected average change in precipitation for the month is determined by dividing the average monthly precipitation over the future time frame by the average monthly precipitation over the overlap period. This results in twelve monthly adjustments, or *deltas*, as shown in the Monthly Deltas graph in Figure 2-13.

The monthly deltas are then applied to the daily values for the corresponding month of the year in the *historical daily weather*, as shown in the Historical Daily Weather graph in Figure 2-13. For the gridded data used in the CRWAS hydrology modeling this process is repeated for each grid cell, and for each month of the year. Because the hydrology model (VIC) uses daily data, each day of the month is adjusted by the same change. This process is straightforward because the grid geometry for the historical weather and the climate projections are identical.

For precipitation, which is the example shown in Figure 2-13, the change is expressed as a multiplicative factor. Using January for an example, for each day in every January in the historical daily weather, the daily value is multiplied by the monthly change factor calculated for January. This is repeated for each month of the year to create the *climate-adjusted daily weather*, and the entire process is repeated for the 2070 time frame. For temperature the process is identical except that change is calculated as the difference between the average future conditions and the average historical conditions and is added to the historical daily weather values.

The consumptive use analyses for the Study basins superimposes historical or projected mean monthly temperature and total monthly precipitation for each of the 54 climate stations in the Study area on current irrigated acreage and crop types to estimate CIR. The weather stations are distributed throughout the Study basins, as shown on the maps presented in Section 3.4 and 3.5. Climate-adjusted weather for each of the ten climate projections was developed by adjusting the data at each weather station location by the monthly deltas for the grid cell in which the weather station is located. Just as with adjustments to the gridded weather, change in temperature was expressed as an offset in degrees Celsius and change in precipitation was expressed as a scale factor.

Historical temperature and precipitation StateCU input files were developed as part of the CDSS. The CDSS DMI, TSTool, includes the capabilities to perform addition and scaling operations, and was used to create new mean monthly temperature and total monthly precipitation input files for each of the ten climate projections. The data-centered “command” approach allowed instructions to be created that directed TSTool to perform the analysis for one climate projection; then the commands were duplicated for the other nine projections.

Trend analyses were performed to better understand the spatial aspect of temperature and precipitation changes associated with the climate projections. Maps and tables describing changes in temperature and precipitation compared to historical are presented in Section 3.4.

Climate-Adjusted Natural Flow

Development of climate-adjusted natural flows uses three primary data sets: historical weather, historical natural flows and projected climate conditions. Development of climate-adjusted natural flows proceeds in two principal steps. First, climate-adjusted weather is developed as described above. Next, a hydrology model is used to make two simulations, the first using the observed weather as input, and the second using the climate-adjusted weather as input. The difference between the two sets of simulated flows represents the change in streamflow attributable to the projected change in climate conditions. These changes are applied to the historical water supply condition to produce a *climate-adjusted* water supply condition. This is the water supply condition as if the projected climate conditions had been fully developed at the start of the study period. The development of the climate-adjusted hydrology is illustrated in Figure 2-14.

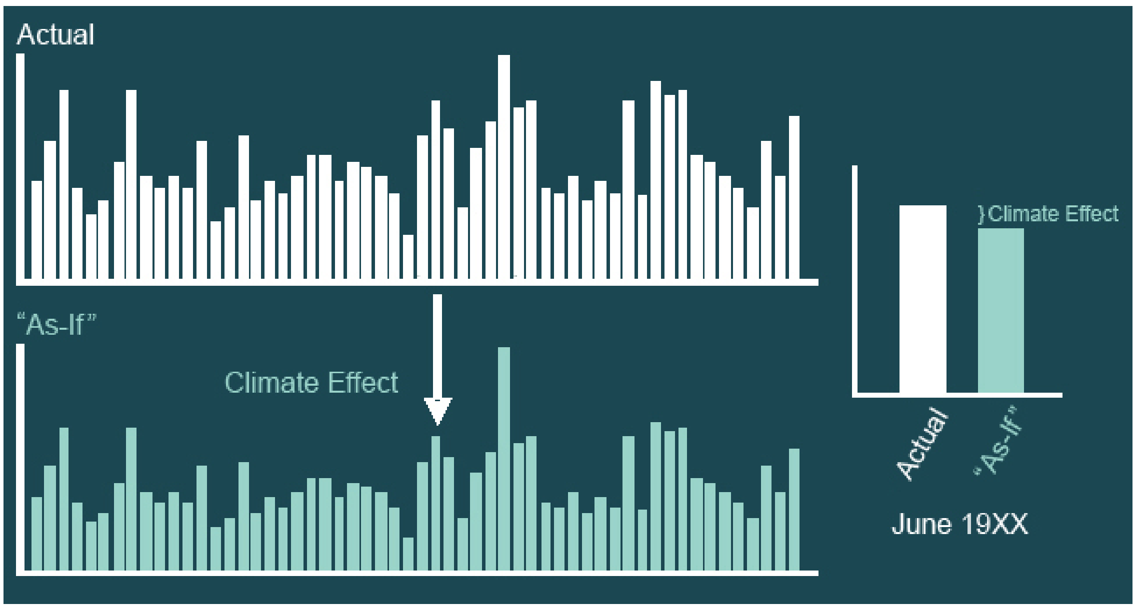


Figure 2-14 – Illustration of development of climate-adjusted water supply

The method illustrated in Figure 2-14 shows the adjustment of a time-series record. For each month of the record the ratio is calculated between the two modeled values of streamflow, one based on observed weather and one based on climate-adjusted weather, and then the historical natural flow for that month is adjusted by that ratio.

The results of this process are 56-year-long, monthly traces of climate-adjusted natural flow for 227 locations required by StateMod to model water availability within Colorado. For each location there will be eleven flow traces: one historical trace, five climate-adjusted traces for the 2040 time frame and five climate-adjusted traces for the 2070 time frame.

Hydrology Modeling

The climate effect on streamflows is estimated using hydrology modeling. A hydrology model (VIC) takes as input weather conditions and returns as output estimates of natural flow. It simulates the significant hydrologic processes that affect the water balance and the physical processes that affect the transport of water and thus affect the timing of flows. Two principal categories of hydrology modeling (statistical models and process models) have been applied to climate change research, and within these two primary modeling categories there are a large number of individual models. The suitability of hydrology models for application to climate change impact studies varies based on both practical and scientific considerations. In addition, there are different choices of how hydrology modeling is used to represent the impacts of climate change.

Statistical hydrology models are based on deriving a functional relationship between streamflow and the climate variables – precipitation, temperature, etc—several of which are typically developed for selected seasons (i.e., monthly or for a set of months, e.g., Dec-Jan-Feb, etc.) In climate change studies, like CRWAS, use of statistical models requires the assumption that the relationships on which the model is based will hold under the climate change scenarios. However, under climate change a seasonal shift is expected in the annual streamflow hydrographs with, for example, warmer temperatures bringing earlier spring runoff (Hayhoe et al., 2004; Barnett et al., 2005; Maurer, 2007). Thus, statistical models are expected to have only a limited application in analyzing streamflows under climate change. CRWAS employed a physical process-based hydrology model, the Variable Infiltration Capacity (VIC) macro-scale hydrology model.

The VIC model is a physically distributed (gridded) macro-scale (regional-scale) hydrology model that consists of a variable-layer soil-vegetation-atmosphere transfer (SVAT) scheme used in general and regional circulation and weather prediction models. The VIC model has two main components – (i) a component to model land-surface (e.g., snow dynamics) and, (ii) a sub-surface modeling component (e.g., infiltration). These two components work in a manner with feedbacks controlling coupled land-surface and sub-surface processes such as infiltration and evapotranspiration.

In the study area, evapotranspiration (ET) is, by far, the most significant water loss process in the hydrologic water balance[12]. As such, the reliability of a hydrology model is directly related to the accuracy and reliability of the representation of ET. In the mountainous terrain of the significant water-producing areas of the Colorado River basin physically-based ET models, as used in VIC, are preferred for basin-scale hydrology modeling because local calibration of vegetation coefficients is not feasible.

Snow accumulation and snow melt are also important processes in simulating the seasonal pattern of streamflow. Because all of the available projections of future climate show that temperature will increase, changes in the pattern of snow accumulation and melt will result. A more physically-based snow model, of the sort used in VIC, provides more confidence that simulations involving changes in temperature will result in realistic changes in snow accumulation and snow melt.

Each VIC grid cell is characterized with parameters describing vegetation and soil. A calibrated set of model parameters for the Colorado River Basin used by Christensen et al. (2004), updated by Wood and Lettenmaier (2006) and then used in Christensen & Lettenmaier (2007) was applied for this study. The land cover data in this parameter set were taken from LDAS (Mitchell, et al., 2004). Changes in vegetation were not simulated in developing the CRWAS climate-impacted natural flows. This assumption does add uncertainty to the results of the

[12] No other losses are represented in the hydrologic model. Losses to deep groundwater are not believed to be significant in the Upper Colorado River basin.

hydrology modeling, but uncertainties about future land cover are hard to resolve at this time because there is limited scientific analysis available on which to base simulation of changes of vegetation in response to climate change. However, uncertainty in the types and mix of vegetation may not introduce a corresponding degree of uncertainty to the overall water balance because the total annual amount of evapotranspiration is primarily a function of the energy available to evaporate water, subject to the limited water supply available in the soil from precipitation.

The land-surface component in the VIC model has detailed underlying physical process models, but the sub-surface component is more conceptual. So in terms of calibration, the focus was to calibrate the VIC sub-surface model. A third component is the routing model that transports simulated flows in VIC grid cells to the outlets of the individual sub-basins of the Colorado River.

The sub-surface model consists of five parameters that control (i) shape of the variable infiltration curve (b_infilt), i.e. the partition of surface runoff versus soil infiltration; (ii) maximum velocity of baseflow in the lowest soil layer in a model grid cell (Dsmax); (iii) soil depth for each of the three model soil layers; and two parameters that define the onset of nonlinear baseflow dynamics in the lowest soil layer – (iv) fraction of maximum soil moisture where nonlinear baseflow occurs (Ws) and (v) fraction of the Dsmax parameter at which nonlinear baseflow occurs (Ds).

The calibrated model for the Colorado River Basin provided excellent fit of simulated and observed streamflows for gage locations covering large basin areas, for example the Colorado River at the Lees Ferry gage. This is expected because of the focus of the studies for which the calibrated model had been developed. Further calibration was performed to estimate effective sub-surface model parameters to improve fit at some smaller basins using the automated optimal parameter estimation algorithm MOCOM (Yapao, et al., 1998). The variables that were used as objective functions in the optimization were correlation coefficient, Nash-Sutcliff efficiency, the ratio of root mean square error to the observed mean, and the absolute difference between the simulated and observed monthly peak flow. The five sub-surface parameters described above were optimized using the MOCOM code for a subset of sub-basins and were used to derive a composite soil file consisting of a combination of cells from the initial calibrated model and the cells with optimized soil parameters. The resulting soil file was used in carrying out the VIC model runs. The degree of agreement between simulated and observed flows varies with scale, with smaller basins showing greater disagreement. There is not sufficient information available to establish the degree to which these differences are due to the model structure and its parameters or to the sparseness of and resulting uncertainty in precipitation data. No change was made to the land-surface parameters from the initial calibrated model though spot comparisons were carried out to test the performance with respect to simulating snow dynamics (snow water equivalent). These showed very good agreement between simulated and observed snow accumulation and ablation when using consistent temperature and precipitation values. Parameters from the routing model were not changed from the initial calibrated model.

Adjusting Natural Flows

The hydrology model was used to estimate the *change* in streamflow caused by a projected *change* in climate. As described above, the climate-adjusted weather was developed based on the observed weather. The hydrology model was run once using the observed weather to obtain a baseline condition. Then, for each climate case, the model was run again with the climate-adjusted weather. The time series of flows resulting from the second run were divided by the time-series of baseline flows to obtain a time series of climate adjustment factors. The time series of climate adjustment factors was multiplied by the time series of CDSS-estimated natural flows to obtain the climate-adjusted natural flows that now could be used directly in StateMod.

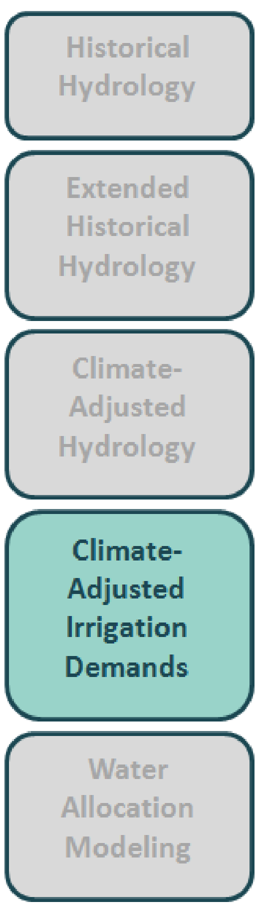
Re-sequencing Climate-adjusted Natural Flows

The climate-adjusted natural flows were re-sequenced into ensembles of 100 56-year traces. Because the climate-adjusted natural flows are associated with a historical year, a 56-year trace of climate-adjusted natural flows can be re-sequenced into a 100-trace ensemble using the same sequences developed as described in Section 2.3.3. One set of climate-adjusted flows resulted for each of the five climate projections associated with each of the two time frames, 2040 and 2070, so a total of ten ensembles, each containing 100 56-year traces of climate-adjusted natural flows, were developed. The ten traces of climate-adjusted natural flows and the ten ensembles of re-sequenced climate-adjusted natural flows make up the alternate hydrology of climate change.

Statistical Analysis of Alternate Hydrology of Climate Change

The ensemble of flow traces in the alternate hydrology of climate change was subject to statistical analysis of the frequency and intensity of wet and dry spells as described in Section 2.3.3. Results of these analyses at selected stations are provided in Appendix C and are summarized in Section 3.4.3.

2.3.5 *Climate-Adjusted Irrigation Demands*



Climate-Adjusted CIR

Crops consume the vast majority of water within the Study Basins. Crop demands, and associated use when provided with an irrigation supply, depend on climate during the growing season. The primary driver of crop demand is temperature. The amount of water crops require from an irrigation source is also dependent on the amount of precipitation available to the crops during the growing season. To allow a robust investigation of water availability under the CRWAS, CIR were adjusted to reflect climate change.

StateCU Consumptive Use Methodology

The consumptive use analyses for the Study basins superimpose historical or projected mean monthly temperature and total monthly precipitation on current irrigated acreage and crop types to estimate CIR. Climate stations that measure temperature and precipitation have good spatial and temporal representation in the Study basins. However, stations that measure wind and solar radiation, required for a detailed daily method such as Penman-Monteith are limited throughout the study basin, and are not present above 6,900 feet in elevation. This is one of the reasons that CDSS adopted the temperature-based monthly Blaney-Criddle approach using StateCU to estimate crop requirements. Because the global climate model archives provide monthly mean temperature and monthly total precipitation values, the Blaney-Criddle method is a robust approach for determining the impacts to crop demands. In addition, it is consistent with the CDSS use of Blaney-Criddle to estimate depletions in the development of natural flows.

CIR is estimated in CDSS first by using the Blaney-Criddle approach to determine potential crop evapotranspiration (ET). Potential crop ET, also called potential crop consumptive use, is an estimate of the maximum amount of water a crop could consume if given a full water supply. CIR is the potential crop ET less the amount of precipitation effective in meeting a portion of the potential crop ET. CDSS has selected the SCS Effective Rainfall method outlined in SCS Technical Release 21 (TR-21). CIR is an estimate of the maximum amount of water a crop could consume if given a full irrigation supply.

For irrigated pasture grass above 6,500 feet elevation, the original Blaney-Criddle method is used with calibrated crop coefficients (Denver Water coefficients) recommended in a comprehensive study of high-elevation lysimeter data sponsored by Denver Water, "Evapotranspiration and Agronomic Responses in Formerly Irrigated Meadows, South Park, Colorado." The basin-specific Historic Crop Consumptive Use Analysis reports detail the CDSS investigation that resulted in selection of the coefficients. Nearly 50 percent of the irrigated acreage in the Study basins is pasture grass grown above 6,500 feet elevation. For irrigated pasture grass grown below 6,500 feet elevation, and for other crops grown in the Study basins, the modified Blaney-Criddle method is used with crop coefficients recommended by TR-21. Because locally calibrated crop coefficients are not available, an elevation adjustment of 10 percent upward for each 1,000 meters above sea level is applied to potential consumptive, as recommended in the ASCE Manuals and Reports on Engineering Practice No. 70, Evapotranspiration and Irrigation Water Requirements (1990) and used by the State Engineer's Office. The use of Denver Water coefficients and a standard elevation adjustment is consistent with other consumptive use analyses performed in the Study basins, including other CWCB modeling efforts and the Yampa/White/Green Roundtable Agricultural Study.

In addition to crop coefficients, growing season "triggers" are defined in TR-21. For most perennial crops, including pasture grass, the growing season start and end dates are based on mean monthly temperature. This is ideal for the CRWAS analysis, as it allows growing seasons to vary with alternate projected monthly temperature.

For the perennial crop alfalfa, the beginning of growing season is defined by mean monthly temperature; however the end of growing season trigger is when the minimum daily temperature drops to 28 degrees Fahrenheit. The down-scale process to minimum daily temperature, and therefore killing frost dates, is much more involved than the downscaling to average monthly temperature described in Section 2.3.4. Therefore, an analysis was performed to determine an appropriate mean monthly temperature for alfalfa that can be used to represent, on average, the killing frost date. Note that the Blaney-Criddle method linearly interpolates between mean monthly temperature values, calculating partial months of growth at the beginning and ending of growing season.

The procedure, documented in the CRWAS technical memorandum "Consumptive Use Analysis – Growing Season Adjustment", resulted in the recommendation to end alfalfa growing season when the mean daily temperature (based on interpolation of mean monthly temperatures) drops below 53 degrees Fahrenheit. This provides the ability for the alfalfa growing season to vary based on both historical and alternate projected monthly temperature, and is important since alfalfa makes up approximately 13 percent of the irrigated acreage in the Study basins.

StateCU Inputs

Estimates of irrigated acreage in the Study basins, by crop type, are used in the CRWAS estimates of CIR under alternate projected climate conditions, as shown in Table 2-11. For CDSS, irrigated acreage is assigned to a water supply ditch, and the analysis is performed on a ditch-wide basis. Ditch structures are paired with the 54 climate stations used in CDSS based on proximity. As discussed previously, there are over 1,200 ditch structures represented in the CDSS analyses of CIR.

Table 2-11 – Current Irrigated Acreage by Crop Type (acres)

Crop Type	Yampa	White	Upper Colorado	Gunnison	San Juan / Dolores	Total
Alfalfa	3,547	3,134	37,965	30,232	26,646	101,524
Pasture Grass<6,500 ft	27,136	16,350	99,097	70,662	55,707	268,952
Orchard and Grapes[1)]	3	0	3,435	6,045	894	10,377
Grains/Vegetables[2)]	400	68	11,831	19,045	4,603	35,947
Corn	0	327	14,847	23,291	1,477	39,942
Pasture Grass>6,500 ft	74,539	6,993	103,672	122,677	134,735	442,616
Basin Totals	105,625	26,872	270,847	271,952	224,062	899,358

1) Orchard and grapes combined for this summary only, CIR is calculated separately for each crop.
2) Spring grains, dry beans, and vegetables are combined for this summary only; CIR is calculated separately for each crop.

CIR estimated at representative climate stations and for irrigated acreage in the Study basins using temperature and precipitation associated with climate projections are summarized and discussed in Section 3.5.

Where to find more detailed information:

For more information, StateCU data sets and associated Historical Crop Consumptive Use Reports for each of the Study basins can be downloaded, along with the StateCU executable, from the CDSS website (http://cdss.state.co.us/).

2.3.6 *Water Allocation Modeling*

StateMod Water Resources Planning Model Methodology

The StateMod water resources planning models were developed and used to investigate how a basin's physical streamflow, water availability, consumptive use, and reservoir use react under various hydrologic conditions. StateMod is an ideal tool for CDSS and CRWAS, as its operations follow the Prior Appropriation Doctrine and Colorado water rights administration.

The StateMod water allocation models are driven by natural flow hydrology. Natural flows represent natural streamflow, absent human effects including agricultural, municipal, domestic, and industrial water uses. StateMod uses nodes and links to simulate the physical systems developed to support these human uses. StateMod simulates water use restricted by physical properties such as head gate and ditch capacities and by reservoir storage and outlet capacities. Finally, legal and administrative conditions are represented in the models, including water rights and operational policies.

StateMod includes a "Base Flow Module" that is used to create a set of natural flows at locations with measured historical stream flows by removing the upstream impact of diversions, return flows, and reservoir storage, releases, evaporation, and seepage. Based on user input regarding drainage area and average annual precipitation, StateMod then automates the distribution of the natural flow gains seen at gaged locations to ungaged tributaries and headwater nodes. The full set of natural flows at both gaged and ungaged locations provides natural inflows to the model at each time step. This set of natural flows were used as the basis for the extended historical hydrology and the climate- adjusted hydrology discussed in Sections 2.3.3 and 2.3.4

StateMod "Simulation Module" operates each time step based on the Modified Direct Solution Algorithm. At each modeled time step, StateMod allocates available streamflow based on the following general steps.

1. Physical water availability is determined at each river node to include both natural inflows and return flows accruing from a prior time step.
2. The most senior direct, instream, storage, or operational water right is identified.
3. Diversions are estimated to be the minimum of the decreed water right, structure capacity, demand, and available flow in the river. For a direct flow or reservoir right, the available flow in the river is the minimum of available flow at the diverting node and at all downstream nodes. By considering flow at downstream nodes, the model preserves the correct supply for downstream senior water rights when calculating the diversion for an upstream junior right. For an instream right, the available flow at each river node within the instream reach is considered.
4. Downstream flows are adjusted to reflect the senior diversion and its return flows.
5. Return flows for future time periods are determined and stored.

6. The process is repeated in order of priority for each successive direct, instream, storage, and operational water right.
7. If new water is introduced to the system from a reservoir's operation or return flows accrue to a non-downstream node, the process is repeated beginning with the most senior direct, instream, storage or operational right whose demand is not fully satisfied.

For irrigation structures, StateMod allows the system efficiency (the product of conveyance efficiency and application efficiency) to vary, up to a specified maximum efficiency. The CIR, supplied by StateCU for every month in the model period, is met out of the simulated head gate diversion, and efficiency (the ratio of consumed water to diverted water) falls where it may – up to the specified maximum efficiency. If the diversion is too small to meet the irrigation requirement at the maximum efficiency, maximum efficiency becomes the controlling parameter. This derivation is termed the Variable Efficiency Algorithm.

StateMod also simulates an on-farm soil moisture balance, representing the ability for excess diverted water to be "stored" in the soil root zone, and consumed in that time step or a subsequent time step. This simulation step is used in CRWAS to determine water availability.

Where to find more detailed information:

For more information regarding distribution of natural flows and model inputs, the Water Resources Planning Model User Manual for each basin can be downloaded, CDSS website (http://cdss.state.co.us/). The User Manual's also describe project operations and administrative agreements and their representations. Section 7 of the StateMod Documentation (Technical Notes) describes the model methodology in detail.

StateMod Current Condition Inputs

For the CRWAS, StateMod Baseline data sets were first used to investigate water use parameters as if current water resource demands, water rights, and projects were in place over the 1950 through 2005 historical hydrologic period. The climate-based input files were then revised, as discussed in Section 2.3.5, to reflect alternate crop demands, irrigation head gate demands, and natural flows associated with each of the ten climate projections.

Baseline data sets that include parameters not directly affected by changes in temperature or natural flows were not revised because they accurately represent current conditions. The following current conditions were not revised from the Baseline data sets for alternate climate projections:

- Absolute direct flow rights, storage rights, instream flow rights, and minimum flow agreements (except minimum fish flows that vary based on hydrology as discussed below)
- Head gate, conveyance, and reservoir capacities
- Reservoir operations including releases for direct uses, hydropower, and flood control

Only currently perfected Colorado water rights with existing infrastructure and demands are represented in the Phase I analyses. StateMod has the capability to reflect conditional water rights associated with identified demand projections and for "what if" scenarios that may be considered in future phases. Water rights, operations and agreements within Colorado are incorporated into the StateMod Baseline data sets, therefore water availability results from the StateMod simulations account for water available to meet future demands within the State.

As presented in Section 3.5, climate-adjusted CIR, and associated irrigation head gate demands, are generally higher than historical demands. The approach of not limiting demands based on historical irrigation practices is an appropriate approach when investigating future operating conditions or varying future hydrology since water availability is based on the legal and physical water available at each diversion point and StateMod operates under this premise. No adjustments were made to either current capacities or current water rights, therefore in some cases demands are not met due to water rights and/or capacity limitations even when water is available. Perfecting conditional water rights, additional water rights, structural changes to increase capacity of diversions and reservoirs, new reservoirs, changes in cropping patterns, dry-up of agricultural lands, and reservoir operational changes are all potential considerations under future efforts.

StateMod Alternate Climate Related Inputs

StateMod time series input files directly affected by climate are revised for each of the climate projections. As discussed below in detail, these input files continue to reflect current practices including irrigated acreage and crop type and reservoir operations, but are adjusted for projected climate conditions. Climate-related StateMod inputs include:

- Natural flows
- CIR
- Irrigation structure head gate demands
- Reservoir forecasting targets (if based on hydrologic year type)
- Fish flow targets (if based on hydrologic year type)

Natural Flows

As discussed in Section 2.3.4, natural flows were adjusted for the 227 locations corresponding to stream gages in the Study basin models for each of the climate projections based on results from the VIC model. Each of the projected climate natural flow data sets was then distributed by StateMod to ungaged and headwater locations using StateMod baseflow module described in Section 2.3.6. These full data sets of baseflows at both gaged and ungaged locations are the foundation for estimating future water availability under future climate scenarios.

Crop Irrigation Requirements

Section 2.3.5 discusses how StateCU was used to revise estimates of CIR for irrigation structures under varying climate projections. CIR is used to estimate head gate demands for irrigation structures under varying climate projections.

Irrigation Structure Head Gate Demands

Hydrology is the best indicator of irrigation conveyance and application efficiency because water supply generally dictates irrigation practices. During wet months and years, there may be excess water when CIR is low. In general, irrigation practices during wet years can result in low system efficiencies when excess diverted water is not necessary to meet CIR. During dry years when water supply is limited, the opposite is true, resulting in high system efficiencies due to the shortage of water. The variation in hydrologic conditions as a result of projected climate will influence the irrigation practices and system efficiencies. The following general approach was used to estimate irrigation structure head gate demands for climate projections:

- *Determine Representative Wet, Dry, and Average Year Efficiencies.* Each irrigation structure was assigned 3 efficiencies for each month that reflect average, wet and dry hydrologic years. These monthly system efficiencies were calculated, for each irrigation structure, based on its historical irrigation demands and water supply for wet, dry, and average hydrologic years. The determination of hydrologic year type were based on natural streamflow at nearby representative "indicator" gages. The procedure for selecting indicator gages is described in detail in the Water Resources Planning Model User Manual documentation for each study basin.

- *Assign Efficiencies to Years based on Projected Climate.* The historical average, wet and dry year monthly efficiencies were then assigned to the appropriate climate-adjusted hydrology years. As expected, for most climate projections, the number of wet years declined and the number of dry years increased.

- *Determine Head Gate Irrigation Demands for Climate Projections.* CIR estimates are divided by average monthly efficiencies considering hydrologic year type, providing estimates of head gate demands for irrigation structures (Section 2.4.4).

Reservoir Forecasting Targets

Four of the USBR reservoirs in the Study basin operate for flood control with operational rules defined by wet, dry, and average forecasted inflow; Green Mountain Reservoir, Ruedi Reservoir, Lemon Reservoir, and Vallecito Reservoir. StateMod mimics the flood control operations by setting monthly storage and release targets, provided by the reservoir operators, for each year in the Study period. For the Baseline dataset, these targets are based on the historical hydrologic year type as determined using nearby indicator gages as described for estimating head gate demands. For the climate projections, these targets were revised based on the year type from the climate projection natural flows. As expected, for most climate projections, the number of years with a wet-year forecast declined, and the number of years with a dry-year forecast increased.

Minimum Flow Targets

CWCB instream flow rights and reservoir minimum bypass agreements do not necessarily vary based on hydrologic year types. Four key locations have flow targets that vary based on the type of year including: reservoir releases to supplement the U.S. Fish and Wildlife Service (USFWS) recommended fish flow through the 15-mile reach of the Colorado River, the U.S. National Park Service (NPS) flow request for its water right through the Black Canyon of the Gunnison National Park, the minimum bypass requirement below Granby Reservoir, and minimum bypass flows downstream of Taylor Park Reservoir:

- The USFWS 15-mile reach recommended flows can be met from natural flow, if available, and are supplemented with releases from several cooperating reservoirs in the Upper Colorado River basin from July 15 through October 31. The CDSS model represents current agreements to supplement river flows from several reservoirs, which assure Colorado water users the ability to develop additional water supplies into the future. Agreements include Ruedi Reservoir releases of 10,000 acre-feet per year in average and wet years, and 5,000 acre-feet per year during dry years. This is supplemented with 10,825 acre-feet per year (referred to as 10825 Water) from Wolford Mountain and Williams Fork reservoirs. Although the current interim agreement allows for some reductions in 10825 Water requirements during drought periods, the model represents full 10825 Water demands. In addition, excess water in the Green Mountain Reservoir Historical Users Pool (HUP Pool) is released to supplement river flows based on historical releases for varying year types. Note that 10825 Water is expected to be stored and released in Granby and Ruedi Reservoirs in the future, and the CDSS model can be revised to reflect that operational change during future routine updates, if these changes are implemented.

- The NPS Black Canyon requested flows vary based on inflows to Blue Mesa Reservoir and water stored in Taylor Park Reservoir, therefore vary with hydrology.

- The minimum bypass requirement below Granby Reservoir is based on hydrologic conditions.

- The minimum bypass requirement from Taylor Park Reservoir has been historically reduced during extremely dry years.

Similar to flood control forecasting for reservoirs for the Baseline dataset, these targets are based on the historical hydrologic year type as determined using nearby indicator gages. For the climate projections, these minimum flow targets were revised based on the year type (wet, average, or dry) from the climate projection natural flows. As expected, for most climate projections, the number of years using a dry-year minimum flow target increased.

Note that the USFWS recommended fish flows in the lower Gunnison River are not represented in the CDSS model as a current demand, as the recommendation is pending the outcome of the EIS process for Aspinall Unit reservoir re-operation. The CDSS model can be revised to reflect that operational change during future routine updates.

The USFWS recommended fish flows and Navajo Reservoir operations associated with the San Juan Recovery Implementation Program (SJRIP) are not included in the CRWAS modeling efforts. Because demands and storage in New Mexico do not affect Colorado's ability to meet their current demands, the CRWAS model representing the San Juan basin does not extend into New Mexico. In addition, the agreements associated with the SJRIP allow Colorado to continue to develop new water supplies, subject to consultation with the USFWS.

Climate Related Inputs Not Revised

During CRWAS Phase I, only demands that were irrigation based were revised to reflect climate projections. It is important to note that transbasin diversion demands were not revised. In addition, the potential increase in municipal demands due to outdoor uses was not considered. In part because the consumptive use associated with municipal demands in study basins is minimal compared to agricultural consumptive use. Transbasin and municipal demands are expected to be revisited during the next phase of the CRWAS project.

Reservoir evaporation is estimated by StateMod based on net average monthly evaporation rates assigned to each modeled reservoir, and reservoir area/capacity relationships. Net monthly evaporation is gross free-water evaporation less precipitation. The net evaporation rates are affected by both temperature and precipitation. Although there are methods for estimating free-water evaporation based on temperature; evaporation rates were not revised during Phase I. This simplification, which for some climate projections may result in underestimating reservoir evaporation, can revisited during subsequence phases.

StateMod Simulation Output

StateMod provides results at every location (node) represented in the model. Available results are the mass-balance components at each node. At all nodes except reservoir locations, inflow components must equal outflow components. Inflows can include water from upstream sources; reservoir releases, return flows, water bypassed for downstream senior uses, etc. plus natural flows not allocated to senior downstream uses. Outflows include flow-through inflow components plus diversions to meet demands or carried to off-channel use. The mass-balance equation at reservoir nodes includes change in storage: inflows less outflows must equal change in storage.

In addition to the mass-balance accounting at each node, StateMod reports results that separate diversion components into consumptive use and return flows. Similarly, reservoir accounting shows the amount stored, evaporated, and released and end-of-month content by reservoir account and for the entire reservoir.

There are several custom reports generated by StateMod that are useful depending on the focus of the analyses. In addition, all the information generated by StateMod is stored in “binary code” output files that save hard-drive space, but cannot be read directly with a text viewer. As discussed in the Supporting Material Section, the CRWAS Data Viewer allows user access to the information generated by StateMod via the web.

Presenting all the information generated by each climate projected StateMod simulation is not practical nor is it necessary since interested stakeholders can choose the specific model output that meets their planning needs through the CRWAS Data Viewer. The following specific model results were selected based on their importance to planning for a future with changing water availability:

- Modeled Streamflow
- Water Available to Meet Future Demands
- Reservoir Use
- Basin Consumptive Use

Modeled streamflow represents water in the river at the location of interest. Physical streamflow is important, because it provides opportunities for exchanges and non-consumptive uses regardless of the legal availability. Modeled streamflow is, essentially, natural flow less upstream depletions.

Water available to meet future demands at a given node is modeled streamflow less water “designated” for current downstream demands with existing water rights. Downstream demands include direct diversions, diversions to storage, and non-consumptive demands such as instream flow rights. As discussed above, conditional rights and the potential operation of compact provisions are not included in the Phase I modeling efforts, therefore water available to meet future demands is only a measure of available flow based on current model-represented demands.

Reservoir storage is important to meeting demands in the Study basin under current climate conditions. Reservoir end-of-month contents show how existing reservoirs store and release under climate projections.

Basin consumptive use includes water that is removed from the system and fully consumed. Basin consumptive use includes agricultural, municipal, and industrial uses within the Study basins. In addition, basin consumptive use includes transbasin water exported from the Study basins to be consumed elsewhere and includes reservoir evaporation. As discussed the method for extracting this information was included in the automation process for select locations, and graphical and tabular results are presented in this report. StateMod results include additional information at each diversion node including demand, diversions from direct rights or from storage, consumptive use of diversions, and shortages. Results for each model run, and at each model location, are available via the web-viewing tool (CRWAS Data Viewer) developed specifically for access to the CRWAS results.

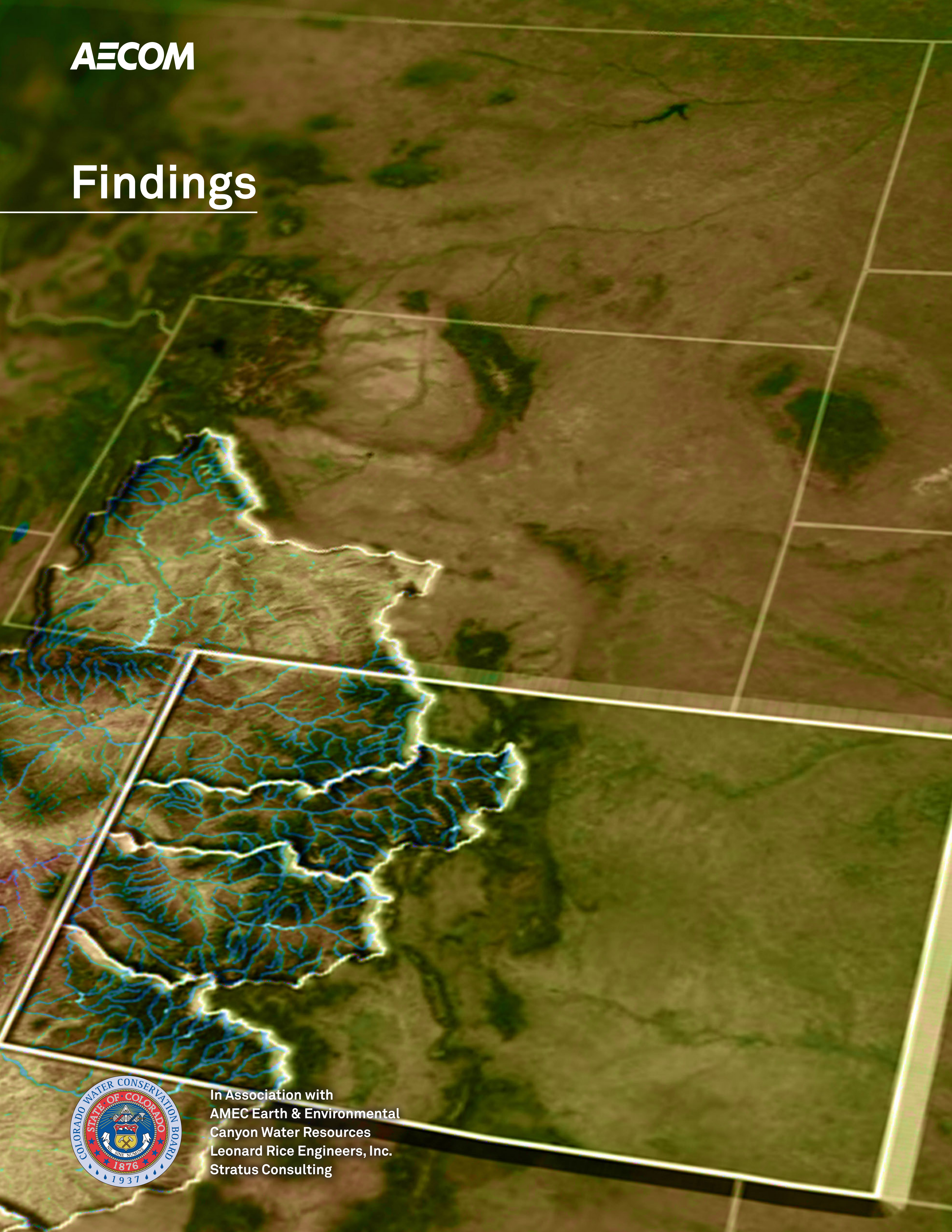
Where to find more detailed information:

For more information on the development of irrigation head gate demands, see the Task 6.6 / 7.11 – *CDSS Automation, Testing, and Application* memorandum available on the Colorado River Water Availability link via the CWCB website (http://cwcb.state.co.us/

For more information, Section 5 of the StateMod Documentation (Technical Notes) describes the output reports and parameters available from a StateMod simulation (http://cdss.state.co.us/). TSTool, and associated user documentation, is available for download on the CDSS website (http://cdss.state.co.us/).

AECOM

Findings



In Association with
AMEC Earth & Environmental
Canyon Water Resources
Leonard Rice Engineers, Inc.
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3 FINDINGS

3.1 Overview

The detailed technical approaches presented in the preceding section were developed in a transparent manner considering the input and direction of CWCB staff and Directors, IBCC and BRT members, the State's CCTAG and representatives of many non-governmental organizations and stakeholders. A major finding for the CRWAS is that the methodology adopted, that built on existing data; existing models; and existing procedures, is a valid technical approach, uniquely suited for the study. The use of readily-available down-scaled climate projection information, the robust VIC hydrology model, and the CDSS processes, models, and data sets provide a comprehensive way to assess water availability and operational effects for historic, extended historic and climate-adjusted hydrologies.

CRWAS findings are presented for the three alternative hydrologic cases: historical hydrology from the 1950 through 2005 study period, alternate historical hydrology incorporating information from tree-rings to allow an extended view of variability, and alternate hydrology associated with potential future climate conditions. Average monthly hydrograph charts and low flow comparison charts are presented in the report and appendices. In addition, these findings can also be accessed, viewed, and downloaded through the CRWAS Data Viewer (www.cwcb.state.co.us) where time series flow charts can be tailored to a user's specific interests. This accessibility of results for each hydrology scenario analyzed at locations throughout the basin specifically addresses the feedback received during the CRWAS public outreach efforts. The information is available for water users and providers to: (1) access model results at specific locations of interest; (2) perform statistical analyses based on selected hydrology and locations and (3) make decisions on which hydrologic datasets to use for planning purposes.

Study results for historic hydrology are provided in combination with climate-adjusted hydrology in the main report and in the appendices for the following parameters:

- Temperature
- Precipitation
- CIR
- Natural Flow
- Modeled Streamflow
- Water Available to Meet Future Demands
- Modeled Reservoir Storage
- Modeled Consumptive Use

The ensemble of 100 56-year-long natural flow traces that constitute the extended historical hydrology is characterized by statistical analyses that allow comparison to the historical record.

Presentation of Findings

The primary chart types used to present quantitative Study findings for the historical and climate-adjusted hydrology parameters listed above are “Average Monthly Hydrograph Charts" and “Low-Flow Comparison Charts”, for which sample figures and descriptions are included below.

Each of the five projections of future climate for a particular time period (2040 or 2070) represent alternative possible future. The average monthly hydrograph charts and the low-flow comparison charts in the following sections and the appendices show the range of those possible futures with respect to historical hydrology conditions that were experienced in the 56 years from 1950 through 2005. Because users are also interested in specific hydrologic year types and varying sequences of year types, time-series results are available for each model run, and at each modeled location, via the CRWAS Data Viewer developed specifically to access CRWAS results.

Comparisons are sometimes made in the text between historical average values and values estimated by averaging the five climate projections for the two CRWAS planning horizons (2040 and 2070) simulated based on the historical variability experienced from 1950 through 2005. When the five climate projections are averaged together for comparison, they are referred to as the five climate projections’ “combined average”. For instance, if historical climate-based average annual values are compared to the average of the five climate projections average annual values, the reference will read “historical average annual values are greater than the five climate projections’ combined average.”

The appendices include tabular and graphical information for 14 climate stations and 42 streamflow locations for various model input and output parameters and results. Figures in the following sections were selected to illustrate general results and conclusions that can be drawn from the full set of figures found in the appendices. In some instances, figure locations were selected because they highlighted a specific result. In other instances, figure locations were selected to include geographic coverage of the study area.

Average Monthly Hydrograph Charts

Figure 3-1 illustrates graphically the effect of projected future climate on the average monthly pattern of flows. This average monthly hydrograph chart shows several pieces of information. The thick black line represents the average monthly hydrograph based on historical conditions; in the case of Figure 3-1 it represents the historical natural flow monthly hydrograph. The estimated average monthly natural hydrographs for the five different projections of future climate are represented in different colors and symbols, listed in the chart legend. The range of average annual values for the five projections, and the average annual historical values, are presented on each graph.

Figure 3-1 and the other monthly hydrographs presented in this section illustrate the historical conditions over the study period of 1950 through 2005 and how those historical conditions would look assuming the projected climate change has occurred. They are not based on the re-sequenced flows

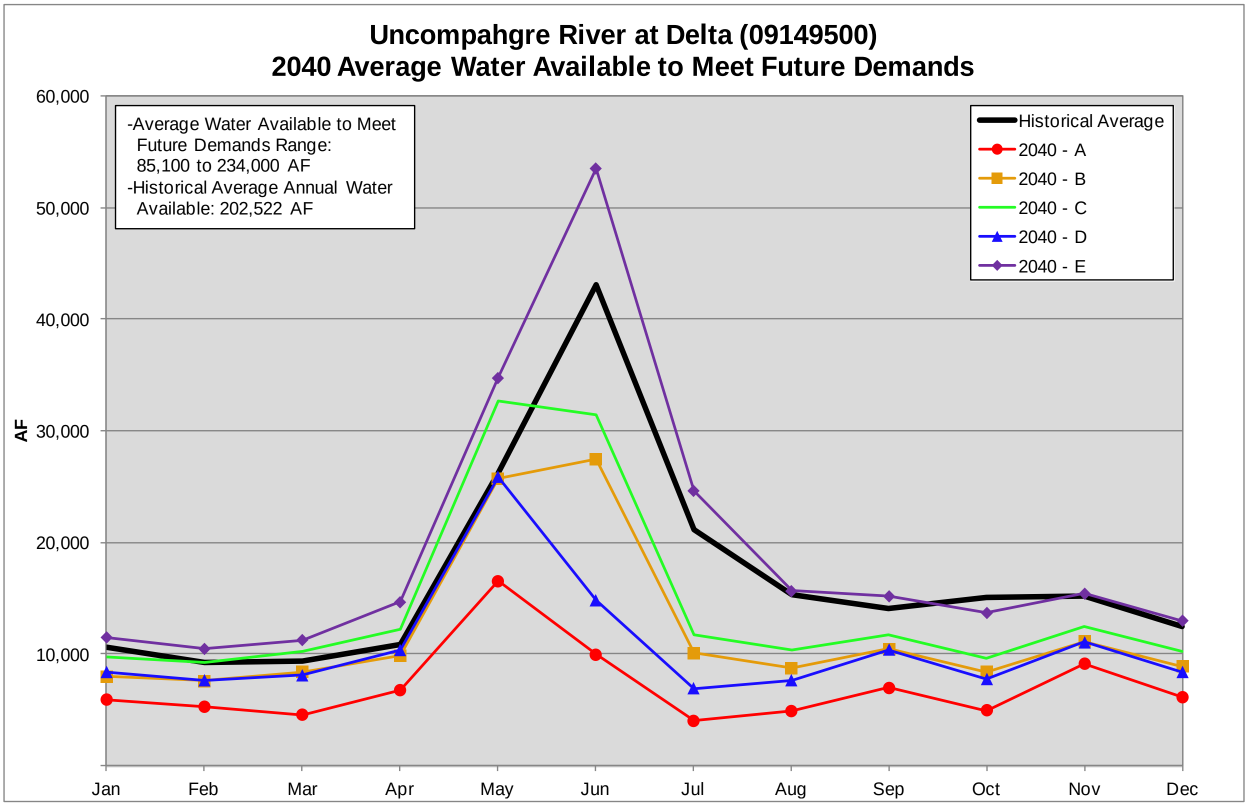


Figure 3-1 - Example Presentation of Findings (Average Monthly Hydrograph Chart)

Low-Flow Comparison Charts

Figure 3-2 illustrates the effect of projected future climate conditions on mean flows and on low-flow events. From left to right, the chart represents four statistics of annual flow: average annual flow over the 56-year study period, the lowest consecutive 2-year average flow in the 56-year study period, the lowest consecutive 5-year average flow in the 56-year study period, and the lowest consecutive 10-year average flow in the 56-year study period. Statistics are provided for historical climate conditions and for each of the climate projections, as indicated in the graph legend.

Figure 3-2 and the other low-flow comparison charts presented in this section illustrate the historical conditions over the study period of 1950 through 2005 and how those historical conditions would look assuming the projected climate change has occurred. They are not based on the re-sequenced flows. Figure 3-2 shows that at the Uncompahgre at Delta location, the historical averages fall within the range of modeled results.

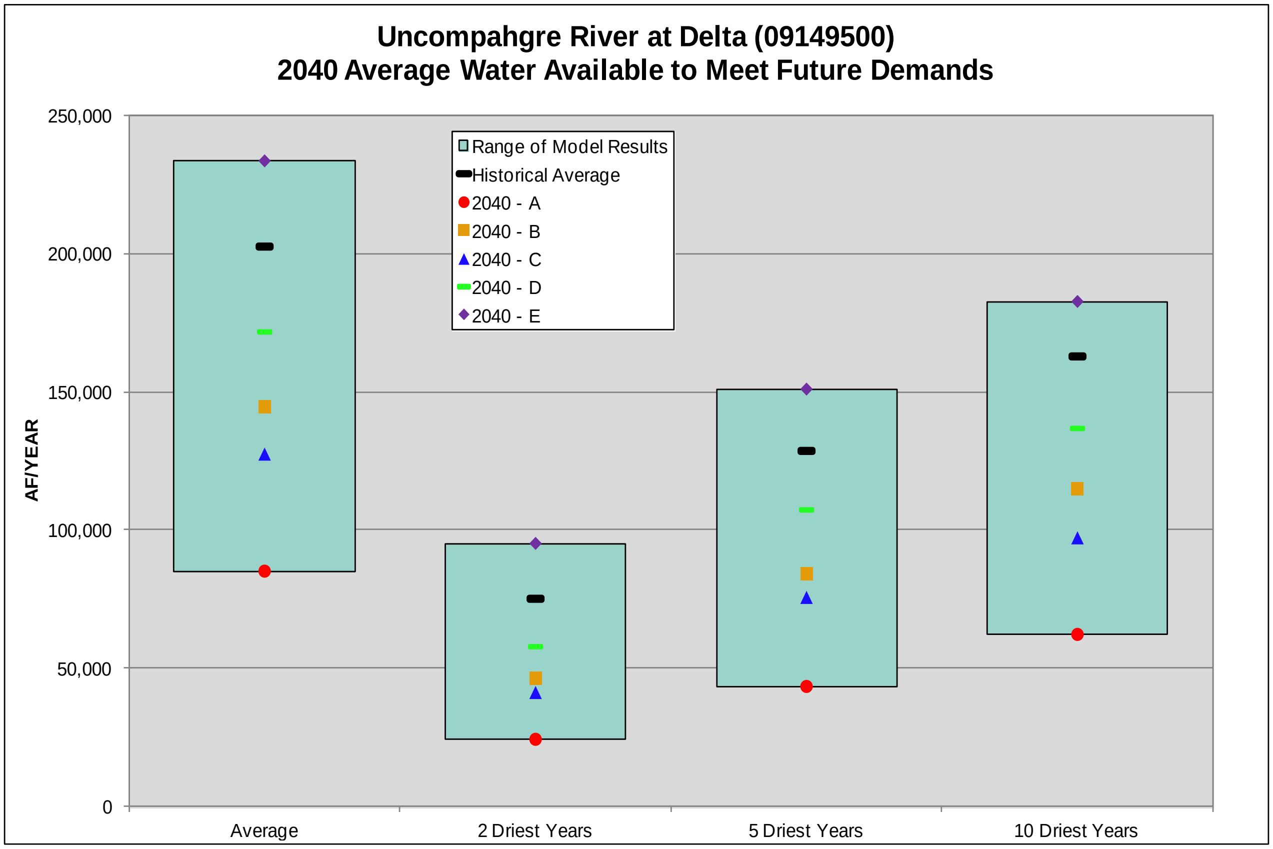


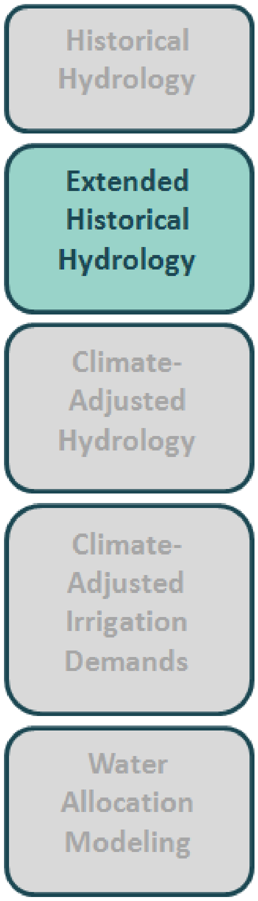
Figure 3-2 - Example Presentation of Findings (Low-Flow Comparison Chart)

3.2 Historical Hydrology

All of the extended and projected streamflows developed by the Study are based on the historical record of naturalized flows and observed weather developed as described in Section 2.3.2. The historical hydrology includes a good representation of wet, dry, and average years and has served historically as the basis for water supply planning in Colorado; it represents one set of hydrologic conditions on which to consider for water supply planning. The historical results are provided along with climate-adjusted results in all the charts or tables that present results of the Study. For many locations and future time frames the historical average annual flows are contained within the range of projected future conditions.

Across the CDSS models' natural flow locations, the longest historical wet spell ranges in length from 4 to 16 years, with only 4 percent longer than 7 years. The longest historical dry spell ranges in length from 3 to 11 years, with 95 percent of the longest spells being 5 or 6 years long. Moving from locations in the northern part of the state toward the south, historic dry spells tend to become shorter and historic wet spells tend to become longer.

3.3 Extended Historical Hydrology



The purpose of the extended historical hydrology is to test the performance of existing (Phase I) and proposed (in Phase II) water rights, infrastructure, projects and natural systems against flow sequences that have not occurred in the historical record but that have a certain likelihood of occurring. The likelihood of future flow sequences was calculated based on information from tree ring records as described in Section 2.3.3 and is represented in the ensemble of 100 56-year traces of natural flows that make up the alternate historical hydrology. The sequence of wet and dry years that will occur over any future period cannot be predicted, but each of the traces in the extended historical hydrology represents one alternative possible future with respect to the distribution and sequencing of wet and dry years, assuming that the conditions reflected in the paleo record are representative of those conditions that will occur in the future. Each of these alternative possible futures (represented by a flow trace) is equally probable, but its precise sequence of flows differs from all other traces (i.e. other possible futures) in the ensemble. Taken together, the traces reflect the statistics gleaned from the paleo record so that, collectively, the extended historical hydrology ensemble can be used to quantify the likelihood of future hydrologic conditions, again assuming that the conditions represented in the paleo record are similar to those in the future.

Statistics of droughts and wet spells provide a relative indication of the degree to which the future performance of man-made and natural systems may be considered more or less favorable. The methods used to develop statistics of droughts and wet spells are described in Section 2.3.3. The results of statistical analyses of spells are discussed here.

The best way to test the performance of man-made systems is through the application of a detailed water resources model, such as the CDSS StateMod models, to the extended historical hydrology (EHH) ensemble of flow traces. Analyses of current water resources systems under current water use levels using the EHH ensemble has been completed as part of the CRWAS; however, except for spell statistics reported here and in Appendix C, the results presented in this report are based on the 56-year historical record or that record adjusted to reflect the estimated impact of projected future climate conditions. Results of modeling analyses using the StateMod models and the EHH ensemble are available through the CRWAS Data Viewer via the CWCB website. The CRWAS Data Viewer also contains the EHH ensemble of baseflow sequences that will allow additional analyses of future projects or water demand levels in subsequent phases of the CRWAS, in other State studies, or in studies performed by other entities.

Where to find more detailed information:

Statistical analyses are described in detail in CRWAS Technical Memorandum Task 6.7 – *Summarize Alternate Historical Hydrology*, and CRWAS Technical Memorandum Phase I (b) – Task 5.3 2 – *Spell Statistics (refinement to CRWAS Phase I Tasks 6.7)* both available at http://cwcb.state.co.us/.

Mean annual flow at selected locations is the average of the annual flow for the historical 56-year period. The historic dry spell is the longest spell of consecutive years in the historical trace that are below the mean annual flow and the historic wet (or surplus) spell is the longest spell of consecutive years in the historical trace that are above the mean annual flow. Return intervals indicate how frequently spells of the same length as the historical spell occur in the EHH. Intensity indicates the average amount, expressed as a percent of mean annual flow, by which flow is greater than (wet spell) or less than (dry spell) the mean flow during a spell. The following summarizes the statistical analyses of the EHH ensemble of natural flow traces:

- The return intervals for a spell as long as the longest historical wet or dry spell for the 1950 through 2005 study period (the historic spell) vary considerably across the 227 CDSS natural flow locations.

- For small tributaries that had shorter historic wet or dry spells, those spells tend to recur more frequently. For small tributaries that had longer historic spells, those spells tend to recur less frequently. In other words, the estimated frequency of spells appears to be influenced substantially by the length of the historic spells; a statistically unlikely short or long historic spell will translate into a substantially higher or lower frequency (shorter or longer return interval).

- The median return interval in the EHH for a dry spell equal in length to the historic dry spell is about 24 years and the values range from about 12 to 73 years across the middle 90 percent of the CDSS natural flow locations.

- The median return interval in the AHH for a wet spell equal in length to the historic wet spell is 32 years and the values range from about 13 to 100 years for the middle 90 percent of the CDSS natural flow locations.

- The highest and lowest values for the return interval of the historic spells are probably the result of exceptionally long or short historic spells. For example, the lowest and highest return intervals of historic AHH wet spells are 7 and 1,100 years and occur at small streams that recorded historic surpluses lasting 3 and 11 years, respectively while 95 percent the historic surpluses on other streams lasted 5 or 6 years.

- The intensity of EHH dry spells (the average annual deficit) ranges from a minimum of about one-half to a maximum of about three times the intensity of the historic dry spells, with the median value being 10 percent greater than the intensity of the historic dry spells.

- The intensity of EHH wet spells (the average annual surplus) also ranges from about one-half to about three times the intensity of the historic wet spells, but the median value was 20 percent less than the intensity of the historic wet spell.

- A broad range of hydrologic conditions is found in the ensembles of natural flows, so the use of the alternate historical hydrology in water availability analyses using CDSS models will provide information about the impacts of droughts and wet spells of longer duration and greater intensity than those that have occurred during the historical period.

Tables 3-1 and 3-2 show the statistics of dry and wet spells at four principal gages in the Colorado River Basin in Colorado for the historical study period and based on the EHH ensembles. For the historical period the duration and intensity of the longest spell on record (the historic spell) are reported. For the EHH, the return interval and average intensity for a spell of the same length as the historic spell are reported. Moving from north to south, historic droughts generally were shorter and historic wet spells generally were longer during the 1950 through 2005 period. There is not a clear pattern in historic spell intensity. The return interval of a dry spell in the alternate historical hydrology that is as long as the historic dry spell is longer (less frequent) at the northernmost Yampa River and shorter (more frequent) at the southernmost San Juan River. These differences may simply reflect differences in the length of the historic dry spell, as discussed above. Average dry-spell intensities from the alternate historical hydrology do not show a strong pattern but are sometimes larger than the historic intensities. Historic wet spells were generally shorter on the Yampa and Colorado rivers and longer on the Gunnison and San Juan rivers. The return intervals of the historic wet spell in the AHH are similar except for the San Juan, which has a much longer return interval (less frequent wet spells). The average intensities of AHH wet spells are substantially smaller than the historic wet spells.

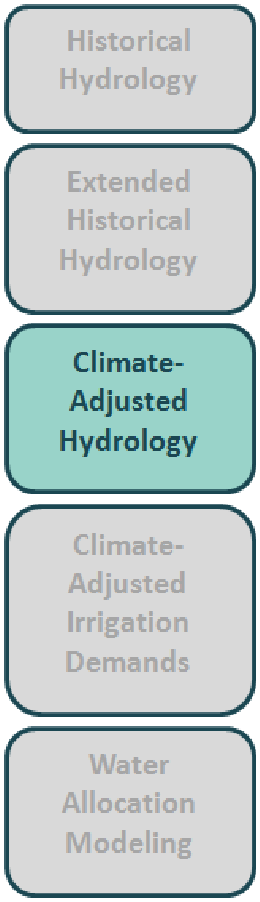
Table 3-1 – Statistics of Dry Spells

	Dry Spells			
	Historic (1950-2005)		Alternate Historical	
	Length	Intensity	Return Interval	Intensity
09239500 Yampa River at Steamboat Springs	6	-23%	49	-26%
09095500 Colorado River near Cameo	6	-19%	28	-24%
09152500 Gunnison River near Grand Junction	5	-33%	16	-30%
09342500 San Juan River at Pagosa Springs	4	-34%	15	-33%

Table 3-2 – Statistics of Wet Spells

	Wet Spells			
	Historic (1950-2005)		Alternate Historical	
	Length	Intensity	Return Interval	Intensity
09239500 Yampa River at Steamboat Springs	5	40%	13	26%
09095500 Colorado River near Cameo	5	46%	18	27%
09152500 Gunnison River near Grand Junction	6	50%	18	31%
09342500 San Juan River at Pagosa Springs	6	43%	45	34%

3.4 Climate-Adjusted Hydrology



3.4.1 *Temperature*

Temperatures based on projected climate changes were compared to historical temperatures at the 54 climate stations used in the CRWAS consumptive use analyses. These 54 climate stations are located throughout the Study basins, as shown in Figure 3-3, and represent areas of agricultural production. Each of these stations has been in existence throughout the 1950 through 2005 study period, and most have been measuring climate data in the same location. Based on station name changes and mapped locations, it was determined that ten of the stations have been relocated within a few miles of the original location.

2040 Projected Temperature

Figure 3-3 shows the increase in average annual temperature based on the 2040 climate projections' combined average compared to historical average annual temperature, based on the 54 climate stations shown in the figure over the 1950 through 2005 study period.

Table 3-3 presents the range of average annual temperature increases from historical values for the 2040 climate projections at selected climate stations. Temperature increases are based on the 1950 through 2005 study period. The climate stations presented in the table were selected to represent a range of elevations and locations of irrigated acreage in the Study Area. The table includes the elevation, plus the location as generally in the northern or southern part of the Study Area. The "Comb. Ave" column represents the projections' combined average increase in temperature, corresponding to the increased temperature shown in Figure 3-3. The spatial distribution of these selected climate stations are shown as red dots in Figure 3-3. As noted above, some stations have been moved during the study period. Of the stations included in Table 3-3, it appears that the Fruita, Delta, and Meeker stations were moved during the study period.

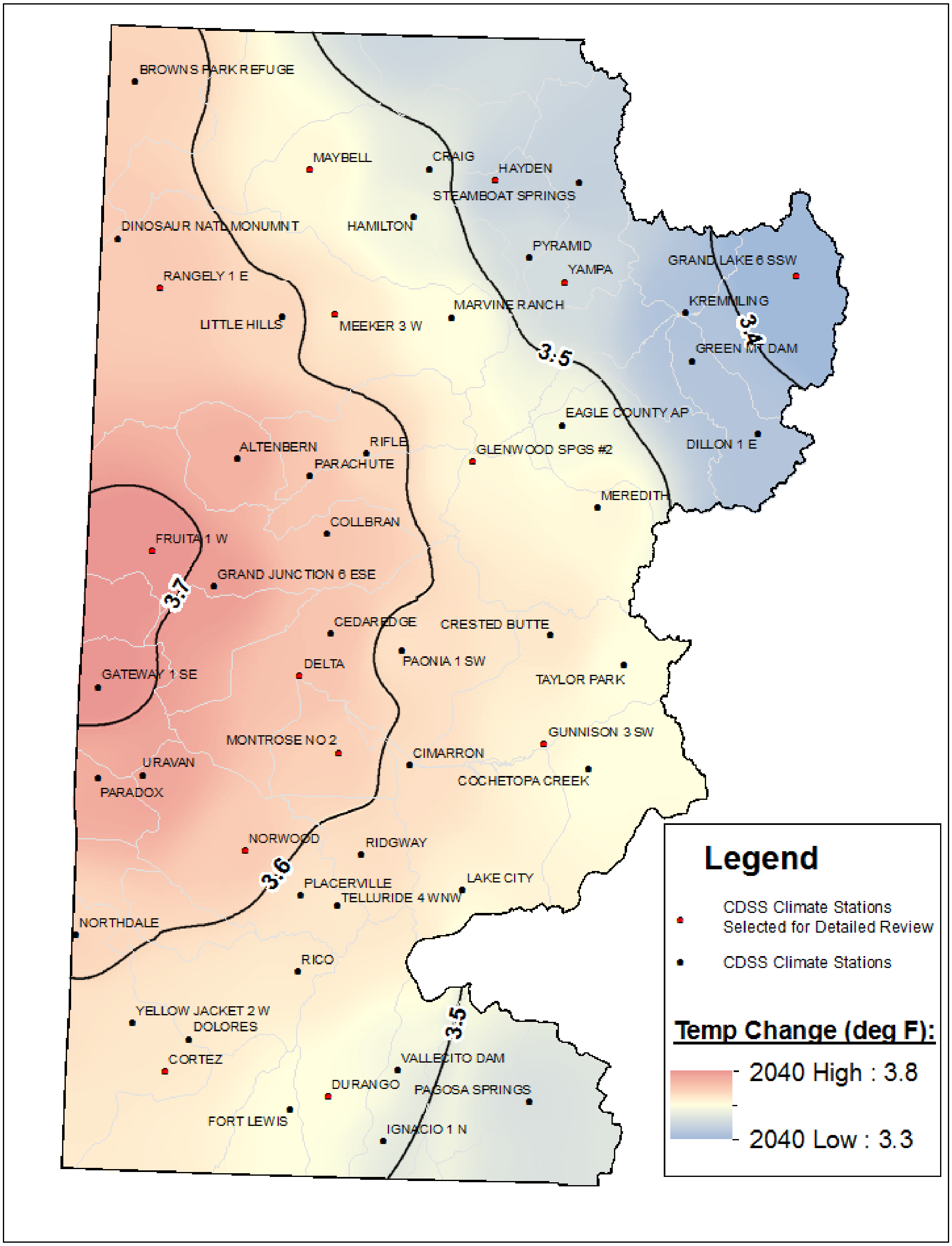


Figure 3-3 – 2040 Projections' Combined Average Annual Temperature Increase from Historical (deg F)

Table 3-3 – 2040 Average Annual Projected Temperature Compared to Historical Temperature

Climate Station	Elev	Location	Historical Average Annual Temp (Deg F)	Increased Temperature from Historical Degrees Fahrenheit for Climate Projections					
				2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave
Fruita 1W	4480	North	50.6	5.3	2.8	4.9	3.6	2.0	3.7
Glenwood 2	5880	North	47.4	5.2	2.8	4.6	3.5	1.8	3.6
Grand Lake 6SSW	8288	North	36.4	5.0	2.7	4.2	3.3	1.6	3.4
Rangely 1E	5290	North	46.8	5.3	2.7	4.8	3.4	1.9	3.6
Meeker 3W	6180	North	44.6	5.2	2.7	4.7	3.4	1.8	3.6
Maybell	5908	North	42.3	5.2	2.7	4.7	3.3	1.9	3.6
Hayden	6440	North	42.7	5.1	2.7	4.5	3.2	1.7	3.5
Yampa	7890	North	39.4	5.1	2.7	4.5	3.3	1.7	3.5
Delta 3E	5010	South	50.5	5.3	2.8	4.7	3.6	1.9	3.6
Montrose No 2	5785	South	49.3	5.3	2.8	4.6	3.5	1.8	3.6
Gunnison 3SW	7640	South	37.7	5.2	2.8	4.5	3.5	1.7	3.6
Cortez	6153	South	48.9	5.3	2.8	4.5	3.4	1.9	3.6
Durango	6592	South	46.9	5.3	2.8	4.4	3.4	1.8	3.5
Norwood	7020	South	45.0	5.3	2.8	4.6	3.5	1.9	3.6
Average [1]			**44.9**	**5.2**	**2.8**	**4.6**	**3.4**	**1.8**	**3.6**

1) Numerical average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

The 14 stations show 2040 average annual increases from historical ranging from 1.6 degrees Fahrenheit for the 2040-E projection at Grand Lake, to 5.3 degrees Fahrenheit for the 2040-A projection at several stations, most in the western and southern portion of the Study Area. The Study Area combined average increase in temperature for the five projections is 3.6 degrees Fahrenheit. The greatest increases for each projection occur at Fruita and Delta. The following general trends can be observed from Table 3-3 and Figure 3-3:

- Each of the five climate projections shows average annual temperature increasing over historical values.
- Temperature generally increases from the eastern to western portion of the Study Area.
- Basin-wide average temperature increases from 1.8 to 5.2 degrees Fahrenheit as shown in Table 3-3.

Figure 3-4 shows the average monthly temperature for each 2040 climate projection compared to the historical average monthly temperature at the Delta climate station over the 1950 through

2005 study period. Similar graphs are included in Appendix A for each selected climate station for the 2040 projections. The temperature graphs for the 2040 projections show that temperature increases each month throughout the Study Area.

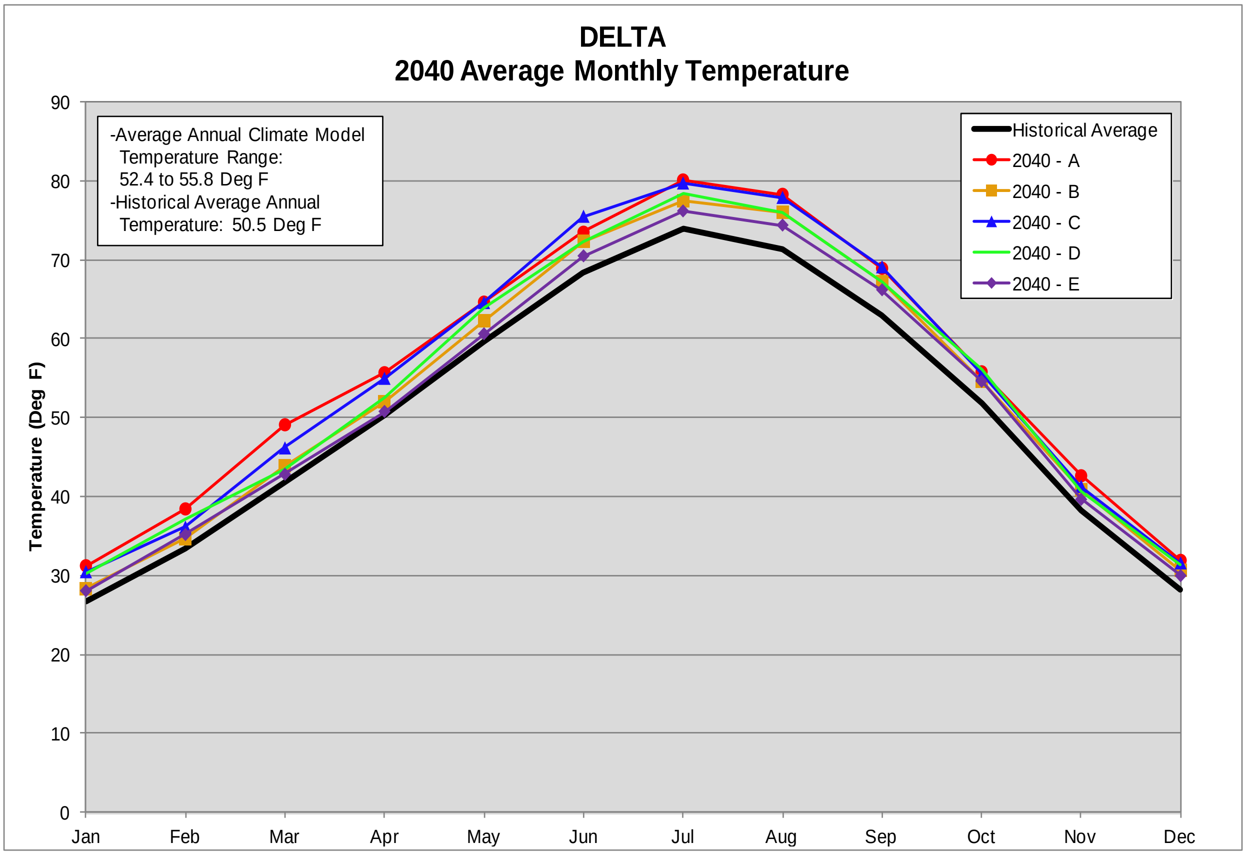


Figure 3-4 – Delta 2040 Average Monthly Temperature Comparison

2070 Projected Temperature

Figure 3-5 shows the increase in average annual temperature based on the 2070 climate projections' combined average compared to historical average annual temperature, based on the 54 climate stations shown in the figure over the 1950 through 2005 study period.

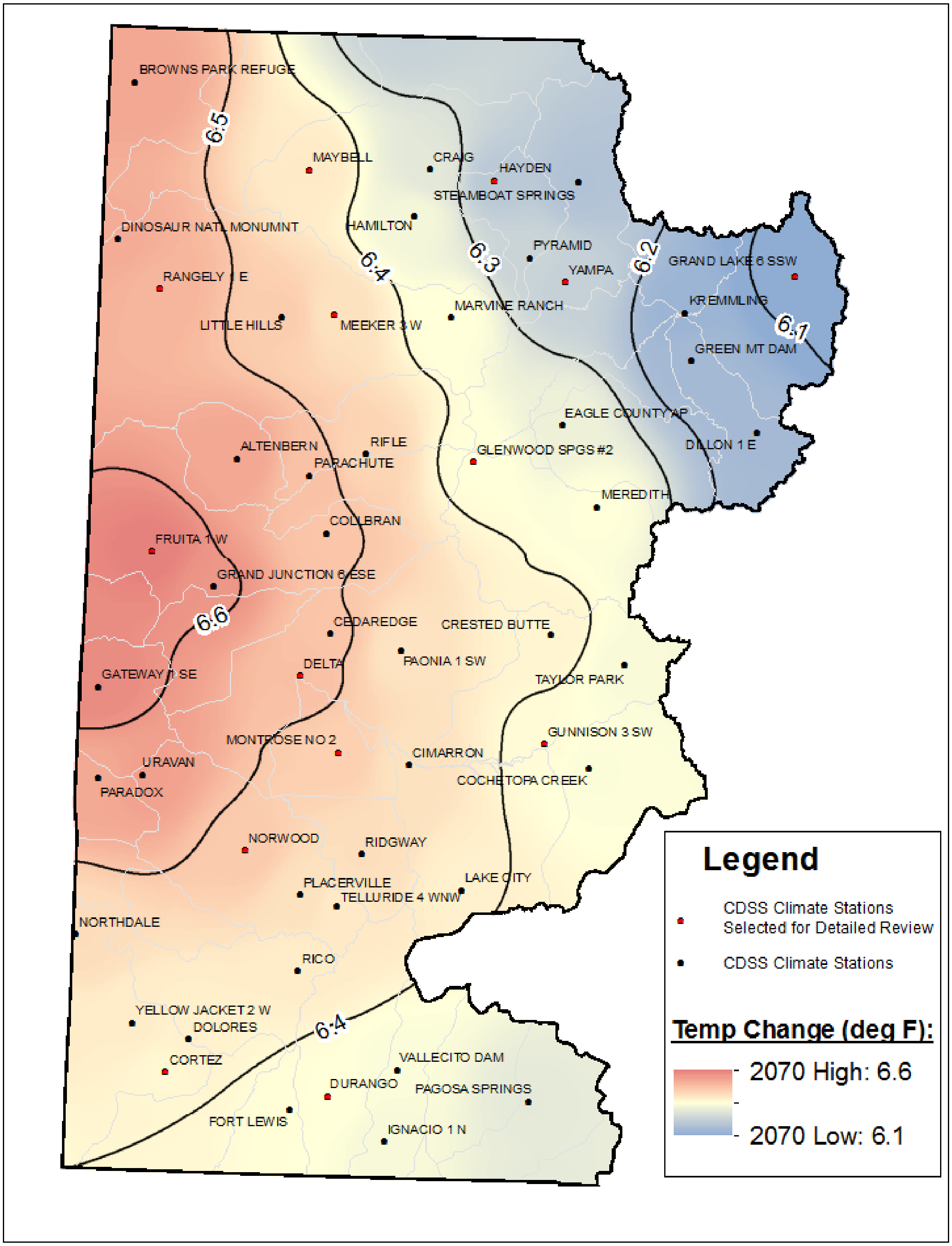


Figure 3-5 – 2070 Projections' Combined Average Annual Temperature Increase from Historical (deg F)

Table 3-4 presents the range of average annual temperature increases from historical values for the 2070 climate projections at selected climate stations. Temperature increases are based on the 1950 through 2005 study period. The “Comb. Ave” column represents the projections’ combined average increase in temperature, corresponding to the increase in temperature shown in Figure 3-5. The climate stations presented in the table are the same as those shown in Table 3-4 for the 2040 projections.

Table 3-4 – 2070 Average Annual Projected Temperature Compared to Historical Temperature

Climate Station	Elev	Location	Historical Average Annual Temp (Deg F)	Increased Temperature from Historical Degrees Fahrenheit for Climate Projections					
				2070-F	2070-G	2070-H	2070-I	2070-J	Comb. Ave
Fruita 1W	4480	North	50.6	8.5	6.6	6.8	4.3	6.9	6.6
Glenwood 2	5880	North	47.4	8.1	6.6	6.6	4.1	6.6	6.4
Grand Lake 6SSW	8288	North	36.4	7.5	6.4	6.4	3.9	6.2	6.1
Rangely 1E	5290	North	46.8	8.4	6.6	6.8	4.3	6.6	6.5
Meeker 3W	6180	North	44.6	8.3	6.5	6.7	4.2	6.5	6.4
Maybell	5908	North	42.3	8.3	6.5	6.7	4.2	6.4	6.4
Hayden	6440	North	42.7	8.0	6.4	6.5	4.1	6.2	6.2
Yampa	7890	North	39.4	8.0	6.5	6.5	4.0	6.3	6.3
Delta 3E	5010	South	50.5	8.2	6.6	6.7	4.2	6.8	6.5
Montrose No 2	5785	South	49.3	8.2	6.6	6.7	4.2	6.7	6.5
Gunnison 3SW	7640	South	37.7	8.0	6.6	6.6	4.1	6.7	6.4
Cortez	6153	South	48.9	7.9	6.5	6.7	4.2	6.6	6.4
Durango	6592	South	46.9	7.9	6.6	6.7	4.2	6.6	6.4
Norwood	7020	South	45.0	8.2	6.6	6.7	4.2	6.8	6.5
Average[1]			**44.9**	**8.1**	**6.5**	**6.7**	**4.2**	**6.6**	**6.4**

1) Numerical average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

The 14 stations show 2070 average annual increases from historical ranging from 3.9 degrees Fahrenheit for the 2070-I projection at Grand Lake to 8.5 degrees Fahrenheit for the 2070-F projection at Fruita. The Study Area combined average increase in temperature for the five projections is 6.4 degrees Fahrenheit. The greatest increases for each projection occur at Fruita and Rangley. The following general trends can be observed from Table 3-4 and Figure 3-5 plus comparison to 2040 average annual increases:

- Each of the five climate projections shows 2070 average annual temperature increasing over historical values and increasing over the 2040 projections.
- Temperature increases from the northeastern to the western portion of the Study Area.
- Basin-wide average temperature increases from 4.2 to 8.1 degrees Fahrenheit as shown in Table 3-4.
- The climate projections' combined average indicates that temperature increases by an additional 2.8 degrees Fahrenheit between the 2040 and 2070 projections.

Appendix A includes graphs showing 2070 projected temperature for each climate station, similar to the example 2040 graph presented in Figure 3-4. As with 2040 average monthly temperature, the 2070 projections show that temperature increases each month throughout the Study Area.

3.4.2 *Precipitation*

Climate projected precipitation was compared to historical precipitation at the 54 climate stations used in the consumptive use analyses. Winter months (November through March) and the months of April through October show different trends, therefore are discussed separately. In addition, climate model experts recognize that there is more uncertainty in the global climate models' ability to predict summer precipitation than winter precipitation. According to the CWCB-sponsored report "Climate Change in Colorado, a Synthesis to Support Water Resources Management and Adaptation, "the scale of global climate models limits their ability to accurately predict the local thunderstorms that dominate rainfall during the summer months in the Study basins." In addition, the report indicates that larger scale systems such as the monsoon-based conditions that strongly influence the southern areas of the State are not well simulated by climate models. Until more detailed global climate models are created that better represent "regional" weather processes that affect temperature and precipitation of the Colorado River basin, the scientific information used in this Study is currently the best available for a study of this nature.

Where to find more detailed information:

Climate Change in Colorado, a Synthesis to Support Water Resources Management and Adaptation available at http://wwa.colorado.edu/.

2040 Projected Precipitation

Table 3-5 presents the historical average winter (November through March) precipitation and the variation from historical values for the 2040 climate projections at selected climate stations over the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent a range of elevations and locations of irrigated acreage in the Study Area. The "Comb. Ave" column represents the projections' combined average percent of historical winter precipitation. Downscaled precipitation is characterized as a percent change from historical precipitation; therefore precipitation results are similarly presented in Table 3-5.

Table 3-5 – 2040 Average Winter (Nov to Mar) Projected Precipitation Compared to Historical Precipitation

Climate Station	Elev	Location	Historical Average Nov-Mar Precip (inches)	Percent of Historical[1] for Climate Projections					
				2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave
Fruita 1W	4480	North	3.42	97%	112%	102%	110%	109%	106%
Glenwood 2	5880	North	6.56	103%	111%	105%	115%	111%	109%
Grand Lake 6SSW	8288	North	4.67	110%	109%	114%	122%	111%	113%
Rangely 1E	5290	North	3.25	106%	111%	103%	115%	109%	109%
Meeker 3W	6180	North	5.68	106%	111%	103%	116%	110%	109%
Maybell	5908	North	4.76	109%	112%	103%	118%	109%	110%
Hayden	6440	North	7.02	109%	111%	107%	121%	111%	112%
Yampa	7890	North	5.93	109%	110%	107%	120%	110%	111%
Delta 3E	5010	South	2.28	98%	110%	104%	112%	110%	107%
Montrose No 2	5785	South	3.07	98%	110%	104%	113%	112%	108%
Gunnison 3SW	7640	South	3.85	102%	112%	105%	116%	112%	109%
Cortez	6153	South	5.13	88%	110%	106%	114%	115%	106%
Durango	6592	South	8.26	92%	111%	107%	116%	114%	108%
Norwood	7020	South	4.95	96%	110%	104%	113%	112%	107%
Average[2]			4.92	102%	111%	106%	116%	111%	109%

1) Less than 100% difference indicates less annual projected rainfall than historical.
2) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-6 shows the 2040 climate projections' combined average increase in precipitation during the winter months of November through March as a percentage of historical average winter precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The Study Area combined average precipitation for the five projections during the months of November through March is 109 percent of historical average. The following general trends can be observed from Figure 3-6 and Table 3-5:

- Average winter precipitation increases from historical for the 2040-B, 2040-C, 2040-D, and 2040-E climate projections.

- Average winter precipitation generally increases for stations in the northern portion of the Study Area for the 2040-A projection.

- Average winter precipitation generally decreases in the southern portion of the Study Area for the 2040-A climate projection.

- The largest increase in the climate projections' combined average winter precipitation occurs at Grand Lake. The largest decrease in winter precipitation occurs at Cortez for the 2040-A projection.

- Basin-wide winter precipitation increases from 102 to 116 percent as shown in Table 3-5. Coupled with the increase in temperature during the winter months, the projections indicate a shift from snow to rain in the early and late winter months.

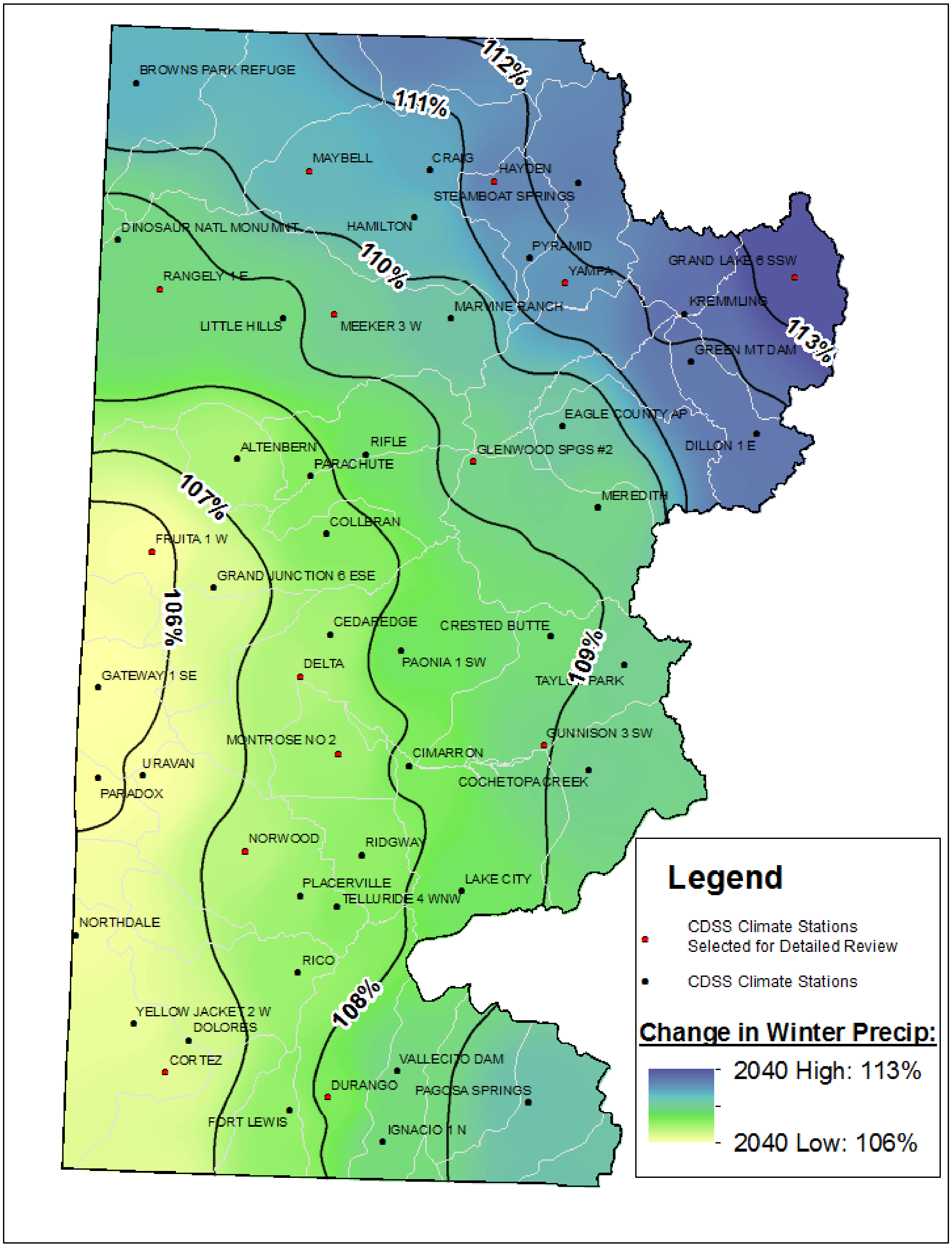


Figure 3-6 – 2040 Projections' Combined Percent of Historical Winter (November - March) Precipitation

Table 3-6 presents the historical average April through October precipitation and the variation from historical values for the 2040 climate projections at selected climate stations over the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent a range of elevations and locations of irrigated acreage in the Study Area. The table includes the elevation, plus the location as generally in the northern or southern part of the Study Area. The "Comb. Ave" column represents the projections' combined average percent of April through October precipitation. The change in precipitation is expressed as the percent change from historical precipitation.

Table 3-6 – 2040 Average Apr through Oct Projected Precipitation Compared to Historical Precipitation

Climate Station	Elev	Location	Historical Average Apr-Oct Precip (inches)	Percent of Historical[1] for Climate Projections					
				2040-A	2040-B	2040-C	2040-D	2040-E	Comb .Ave
Fruita 1W	4480	North	5.37	81%	83%	94%	95%	103%	91%
Glenwood 2	5880	North	10.19	82%	85%	97%	93%	107%	93%
Grand Lake 6SSW	8288	North	9.38	80%	89%	102%	94%	112%	95%
Rangely 1E	5290	North	6.77	82%	86%	96%	99%	104%	94%
Meeker 3W	6180	North	10.41	82%	87%	98%	97%	105%	94%
Maybell	5908	North	7.53	83%	88%	99%	100%	106%	95%
Hayden	6440	North	9.95	81%	90%	102%	98%	107%	96%
Yampa	7890	North	10.43	81%	89%	101%	96%	107%	95%
Delta 3E	5010	South	5.13	82%	83%	95%	93%	104%	91%
Montrose No 2	5785	South	6.49	82%	82%	95%	93%	104%	91%
Gunnison 3SW	7640	South	6.73	82%	83%	98%	91%	106%	92%
Cortez	6153	South	7.57	82%	79%	94%	94%	102%	90%
Durango	6592	South	11.48	84%	80%	96%	92%	103%	91%
Norwood	7020	South	10.14	82%	82%	96%	93%	104%	91%
Average[2]			8.40	82%	85%	98%	95%	105%	93%

1) Less than 100% difference indicates less annual projected rainfall than historical.
2) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-7 shows the 2040 climate projections' combined average increase in precipitation during the during the months of April through October as a percentage of historical average precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The Study Area combined average precipitation for the five projections during the months of April through October is 93 percent of historical average. The following April through October precipitation trends can be observed from Figure 3-7 and Table 3-6.

- April through October precipitation decreases from historical for the 2040-A, 2040-B, and 2040-D climate projections throughout the Study Area.

- April through October precipitation increases for the 2040-E projection throughout the Study Area.

- April through October precipitation generally increases for the 2040-C climate projection in the northern portion of the Study Area (Grand Lake, Hayden, and Yampa), and decreases at stations in the southern portion of the Study Area.

- Basin-wide April through October precipitation is from 82 to 105 percent of historical as shown in Table 3-6.

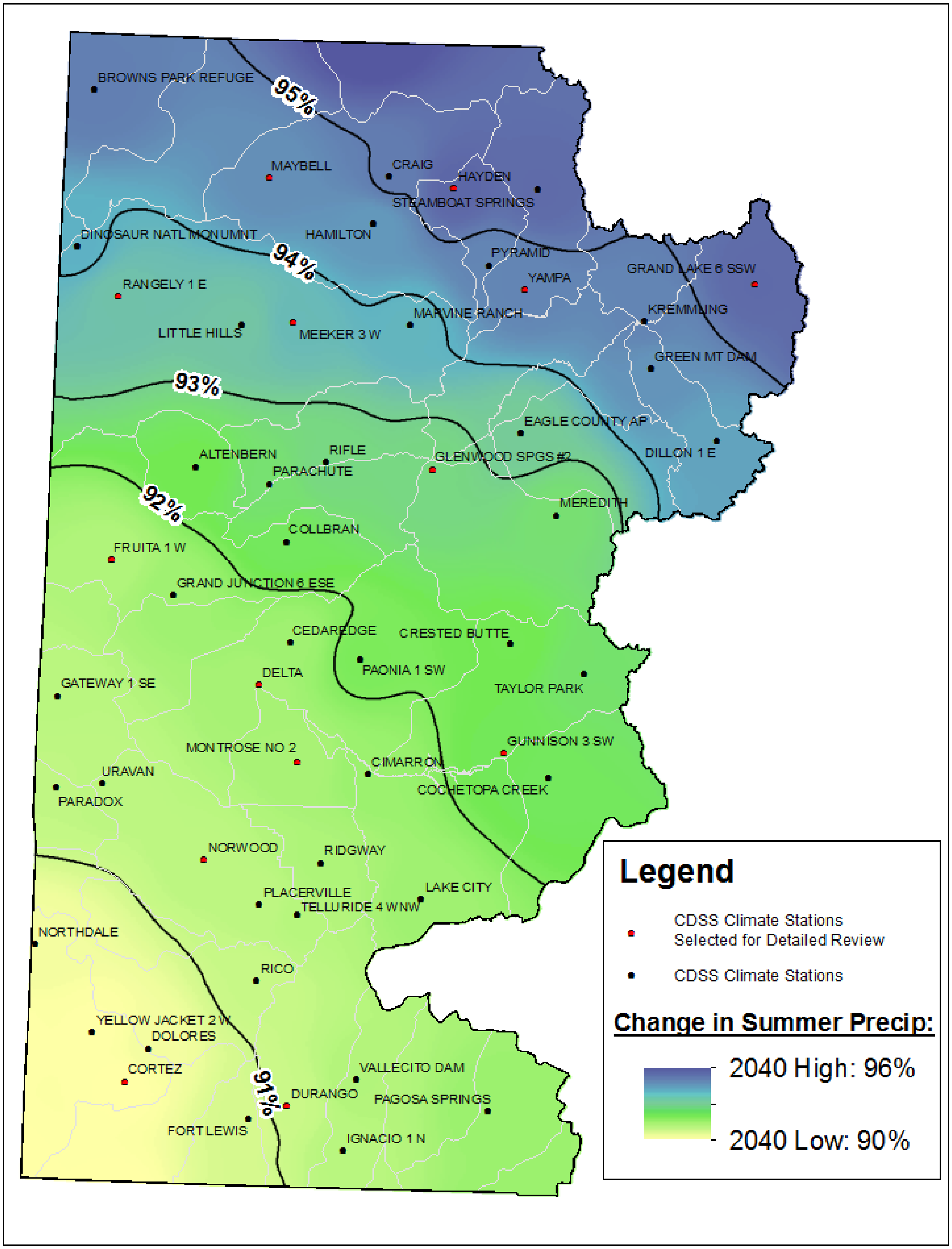


Figure 3-7 – 2040 Projections' Combined Percent of Historical April through October Precipitation

Figure 3-8 shows the average monthly precipitation for each 2040 climate projection compared to the historical average monthly precipitation for the 1950 through 2005 study period at the Delta climate station. Similar graphs are included in Appendix B for each selected climate station for the 2040 projections. As with Figure 3-8, figures in Appendix B generally show the following:

- The 2040 climate projections generally show precipitation greater than historical averages during the winter months from November through March throughout the Study Area.

- Most of the climate projections generally show precipitation less than historical averages during the irrigation season, from May through October. A clear exception is the 2040-E projection, which shows increased precipitation in May, June, July, and August at locations throughout the Study Area. Locations in the southern portion of the Study Area show dryer summers for most projections.

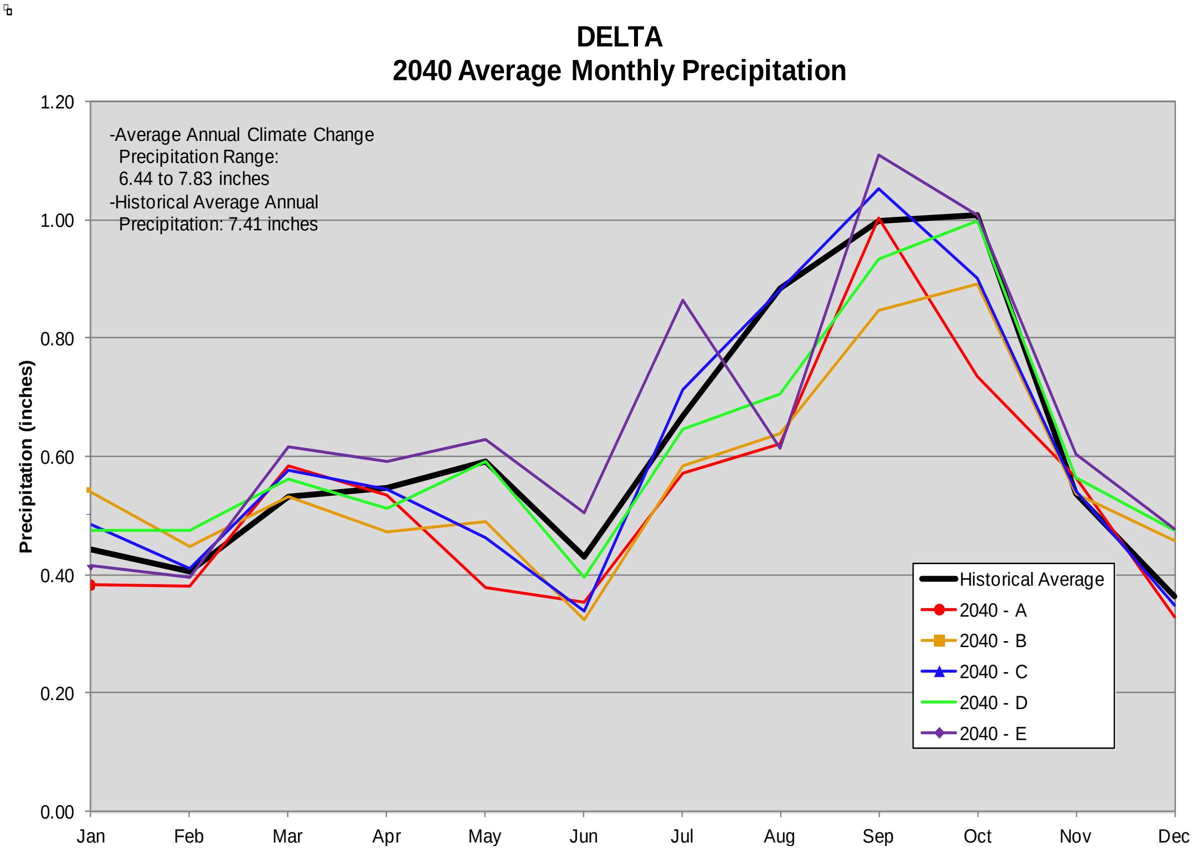


Figure 3-8 – Delta 2040 Average Monthly Precipitation Comparison

2070 Projected Precipitation

Table 3-7 presents the historical average winter (November through March) precipitation and the variation from historical values for the 2070 climate projections at selected climate stations over the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent a range of elevations and locations of irrigated acreage in the Study Area. The “Comb. Ave” column represents the projections’ combined average percent of historical winter precipitation. The table includes the elevation, plus the location as generally in the northern or southern part of the Study Area.

Table 3-7 – 2070 Average Winter (Nov through Mar) Projected Precipitation Compared to Historical Precipitation

Climate Station	Elev	Location	Historical Average Nov-Mar Precip (inches)	Percent of Historical[1] for Climate Projections					
				2070-F	2070-G	2070-H	2070-I	2070-J	Comb. Ave
Fruita 1W	4480	North	3.42	92%	98%	105%	108%	119%	104%
Glenwood 2	5880	North	6.56	102%	105%	111%	109%	128%	111%
Grand Lake 6SSW	8288	North	4.67	112%	111%	116%	114%	136%	118%
Rangely 1E	5290	North	3.25	96%	103%	107%	110%	127%	109%
Meeker 3W	6180	North	5.68	99%	105%	109%	111%	128%	110%
Maybell	5908	North	4.76	99%	107%	109%	112%	131%	111%
Hayden	6440	North	7.02	105%	111%	113%	114%	134%	116%
Yampa	7890	North	5.93	105%	109%	112%	113%	133%	114%
Delta 3E	5010	South	2.28	95%	98%	104%	106%	122%	105%
Montrose No 2	5785	South	3.07	96%	97%	104%	106%	122%	105%
Gunnison 3SW	7640	South	3.85	102%	104%	110%	107%	128%	110%
Cortez	6153	South	5.13	91%	88%	100%	104%	117%	100%
Durango	6592	South	8.26	96%	92%	102%	104%	121%	103%
Norwood	7020	South	4.95	95%	95%	102%	105%	120%	104%
Average[2]			4.92	99%	102%	108%	109%	127%	109%

1) Less than 100% difference indicates less annual projected rainfall than historical.
2) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-9 shows the 2070 climate projections' combined average increase in precipitation during the winter months of November through March as a percentage of historical average winter precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The Study Area combined average precipitation for the five projections during the months of November through March is 109 percent of historical average. The following general trends can be observed from Table 3-7 and Figure 3-9, plus comparison to 2040 average annual increases:

- Average winter precipitation generally increases from historical for the 2070-H, 2070-I, and 2070-J climate projections.
- Average winter precipitation generally increases for stations in the northern portion of the Study Area for the 2070-G climate projection, and generally decreases for stations in the southern portion of the Study Area.
- Average winter precipitation both increases and decreases for the 2070-F projection depending on location, generally decreasing in the southern portion of the Study Area.
- The largest increase in average winter precipitation occurs at Grand Lake for the 2070-J climate projection. The largest decrease in winter precipitation occurs at Cortez for the 2070-F climate projection.
- Basin-wide winter precipitation is from 99 to 127 percent of historical as shown in Table 3-7.
- The range of winter precipitation between the five 2070 projections is greater than the range between the five 2040 projections. Coupled with the increase in temperature during the winter months, the projections indicate a shift from snow to rain in the early and late winter months.

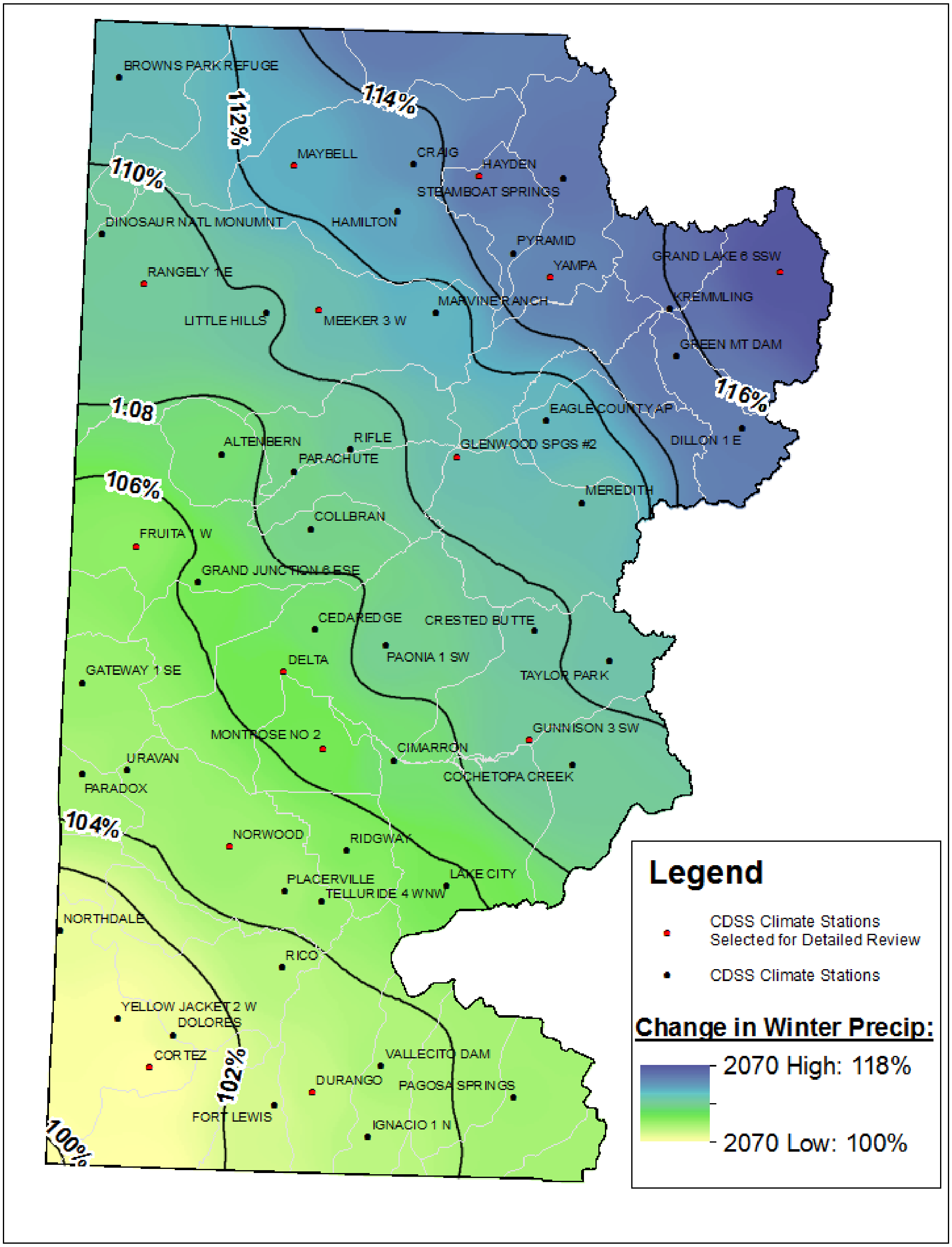


Figure 3-9 – 2070 Projections' Combined Percent of Historical Winter (November - March) Precipitation

Table 3-8 presents the historical average April through October precipitation and the variation from historical values for the 2070 climate projections at selected climate stations over the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent the range of elevations and locations of irrigated acreage in the Study Area. The "Comb. Ave" column represents the projections' combined average percent of April through October precipitation. The table includes the elevation, plus the location as generally in the northern or southern part of the Study Area.

Table 3-8 – 2070 Average Apr through Oct Projected Precipitation Compared to Historical Precipitation

Climate Station	Elev	Location	Historical Average Apr-Oct Precip (inches)	Percent of Historical[1] for Climate Projections					
				2070-F	2070-G	2070-H	2070-I	2070-J	Comb. Ave
Fruita 1W	4480	North	5.37	82%	101%	94%	91%	93%	92%
Glenwood 2	5880	North	10.19	92%	95%	96%	100%	96%	96%
Grand Lake 6SSW	8288	North	9.38	105%	94%	98%	116%	105%	103%
Rangely 1E	5290	North	6.77	89%	102%	96%	98%	104%	98%
Meeker 3W	6180	North	10.41	91%	100%	95%	100%	105%	98%
Maybell	5908	North	7.53	94%	103%	96%	102%	110%	101%
Hayden	6440	North	9.95	101%	99%	96%	107%	112%	103%
Yampa	7890	North	10.43	99%	97%	96%	107%	107%	101%
Delta 3E	5010	South	5.13	88%	98%	97%	93%	91%	93%
Montrose No 2	5785	South	6.49	88%	96%	95%	93%	90%	92%
Gunnison 3SW	7640	South	6.73	91%	93%	94%	100%	92%	94%
Cortez	6153	South	7.57	90%	95%	93%	85%	86%	90%
Durango	6592	South	11.48	90%	93%	94%	90%	87%	91%
Norwood	7020	South	10.14	87%	97%	94%	92%	90%	92%
Average[2)]			8.40	93%	97%	95%	99%	98%	96%

1) Less than 100% difference indicates less annual projected rainfall than historical.
2) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-10 shows the 2070 climate projections' combined average increase in precipitation during the during the months of April through October as a percentage of historical average precipitation over the 1950 through 2005 study period, based on the 54 climate stations used in the CDSS modeling. The Study Area combined average precipitation for the five projections during the months of April through October is 96 percent of historical average. The following general trends can be observed from Table 3-8 and Figure 3-10, plus comparison to 2040 average annual increases:

- April through October precipitation generally decreases from historical for the 2070-H climate projection. This projection shows little variation throughout the Study Area. Other climate projections show both increases and decreases in April through October precipitation.

- April through October precipitation generally decreases for the 2070-F climate projection, with the exception of Grand Lake and Hayden climate station locations.

- The 2070 projections show a greater range of April through October precipitation than 2040 projections. For every location, the climate projections' combined average is higher in 2070 than 2040.

- The range of April through October precipitation between the five 2070 projections is less than the range between the five 2040 projections.

- Basin-wide April through October precipitation is from 93 to 99 percent of historical as shown in Table 3-8.

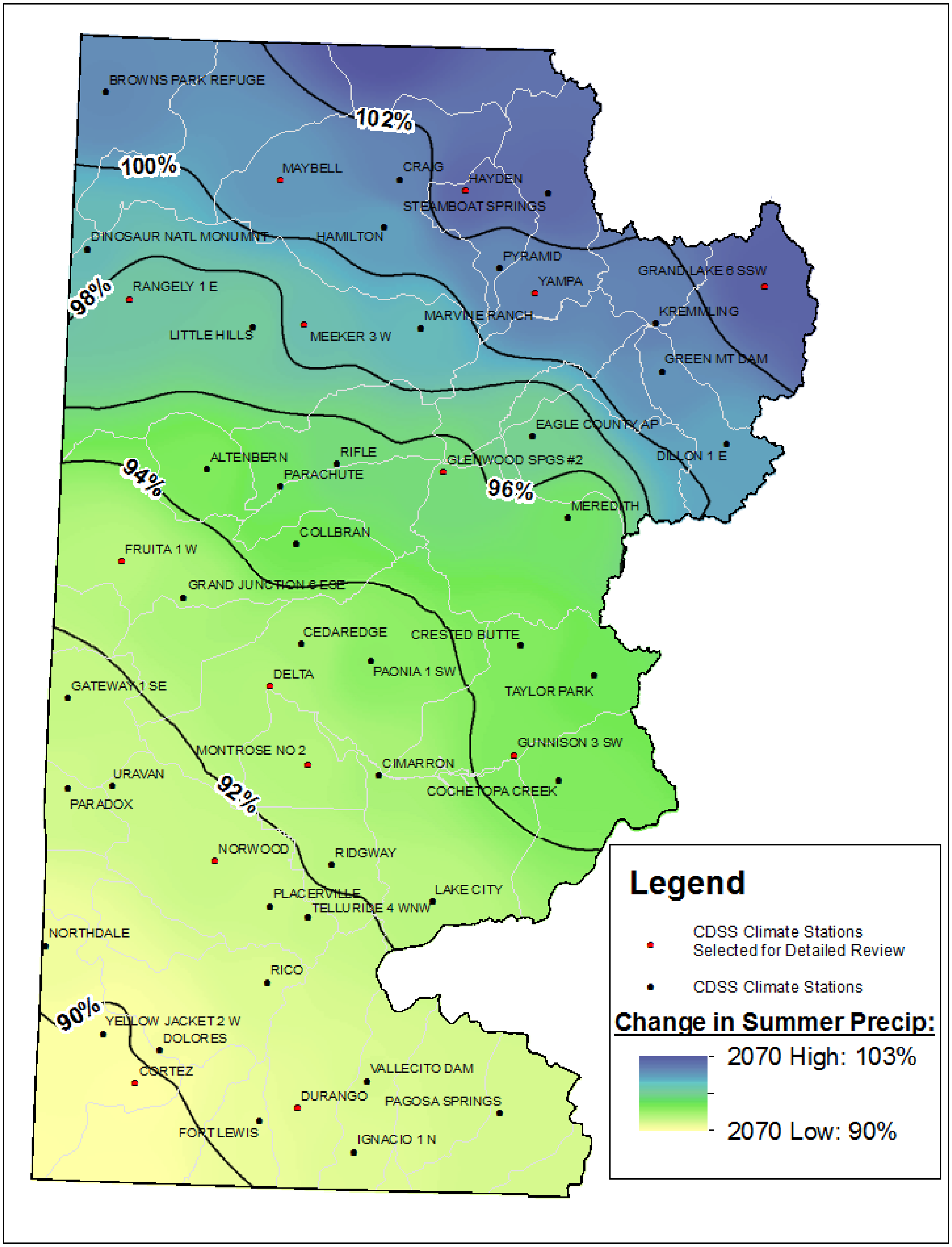


Figure 3-10 – 2070 Projections' Combined Percent of Historical April through October Precipitation

Appendix B includes graphs showing 2070 projected precipitation for each climate station, similar to the example 2040 graph presented in Figure 3-8. Figures in Appendix B generally show the following:

- Similar to the 2040 projections, 2070 projected precipitation is generally higher in the winter months than historical, and less in the summer months than historical.

3.4.3 *Natural Flow*

The StateMod water allocation models are driven by natural flow hydrology. Natural flows represent natural flow, absent human effects including agricultural, municipal, domestic, and industrial water uses. As discussed in Section 2.3.4, projected natural flow was estimated for each of the 2040 and 2070 climate projections at the 227 gage locations where inflow is introduced to the StateMod models. Some general findings include:

- Annual natural flow increases in some possible futures but decreases in others.
- At over 80 percent of the sites, the majority of climate cases suggest a decrease in annual flow for both time frames.
- Annual flow is more likely to increase in parts of the Yampa River basin and in some higher elevation watersheds.
- Annual flow is more likely to decrease in southwestern watersheds and at lower elevations
- At over 90 percent of locations all climate cases showed a shift toward earlier runoff but at all locations some climate cases showed a shift toward earlier runoff

2040 Natural Flow

Figures 3-11 through 3-13 show the seasonal variation in natural flow at three Colorado River stream gage locations from upper basin to lower basin (Colorado River Near Grand Lake, Colorado River at Dotsero, and Colorado River near Cameo) over the 1950 through 2005 study period for the historical model, and for the models representing demands and natural flows adjusted for the 2040 climate projections.

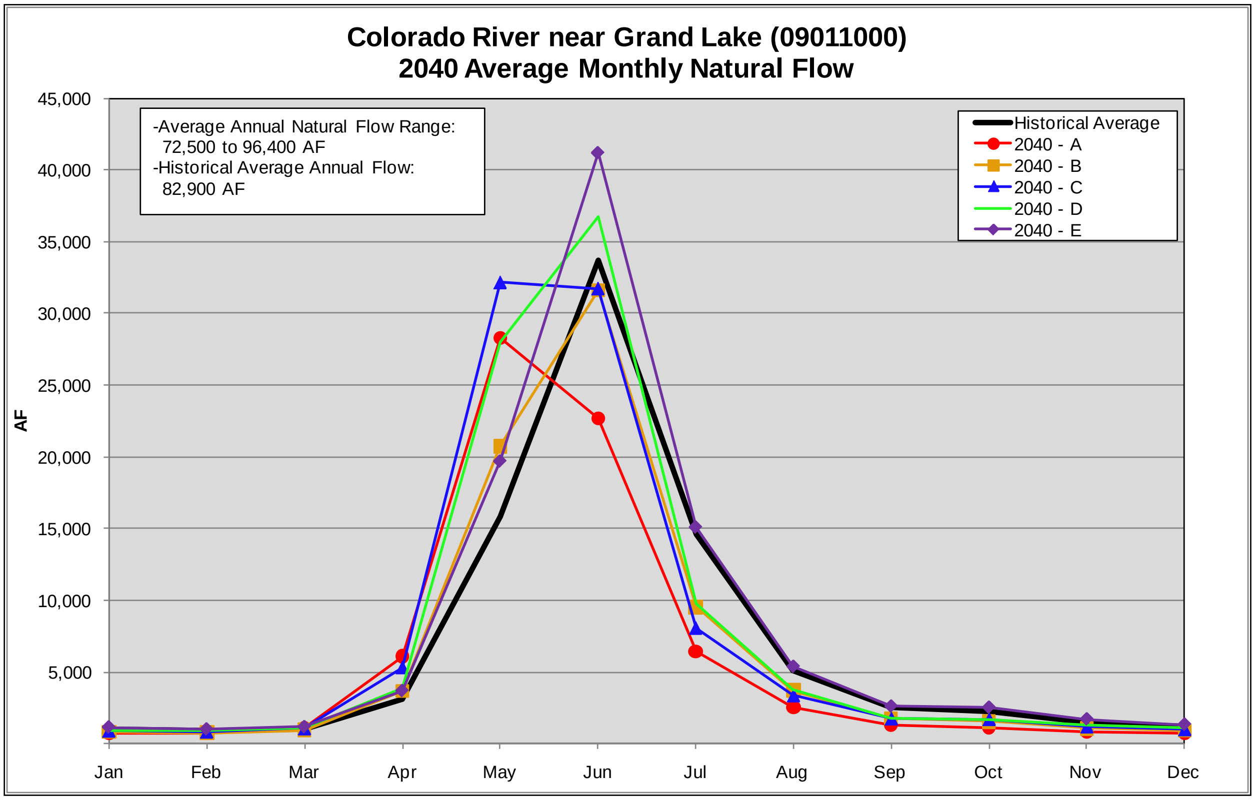


Figure 3-11 – Colorado River near Grand Lake - 2040 Average Monthly Natural Flow

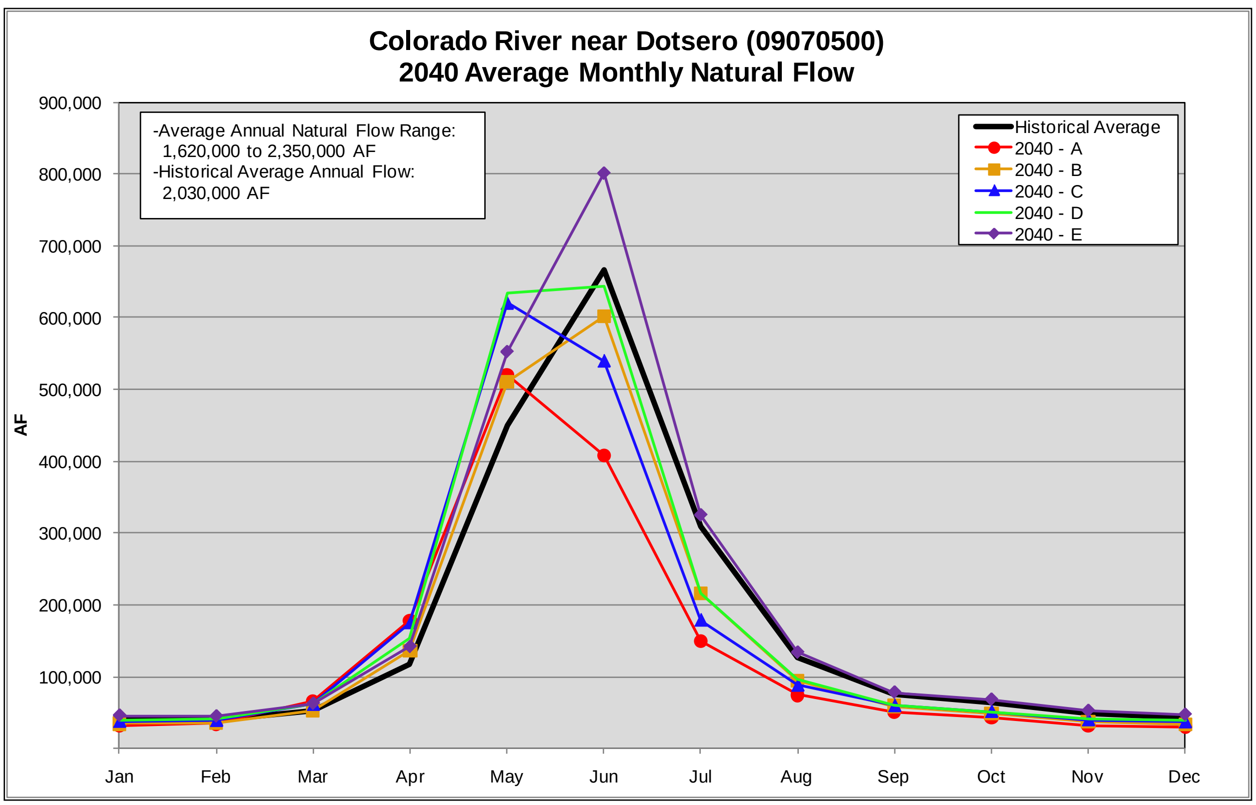


Figure 3-12 – Colorado River at Dotsero - 2040 Average Monthly Natural Flow

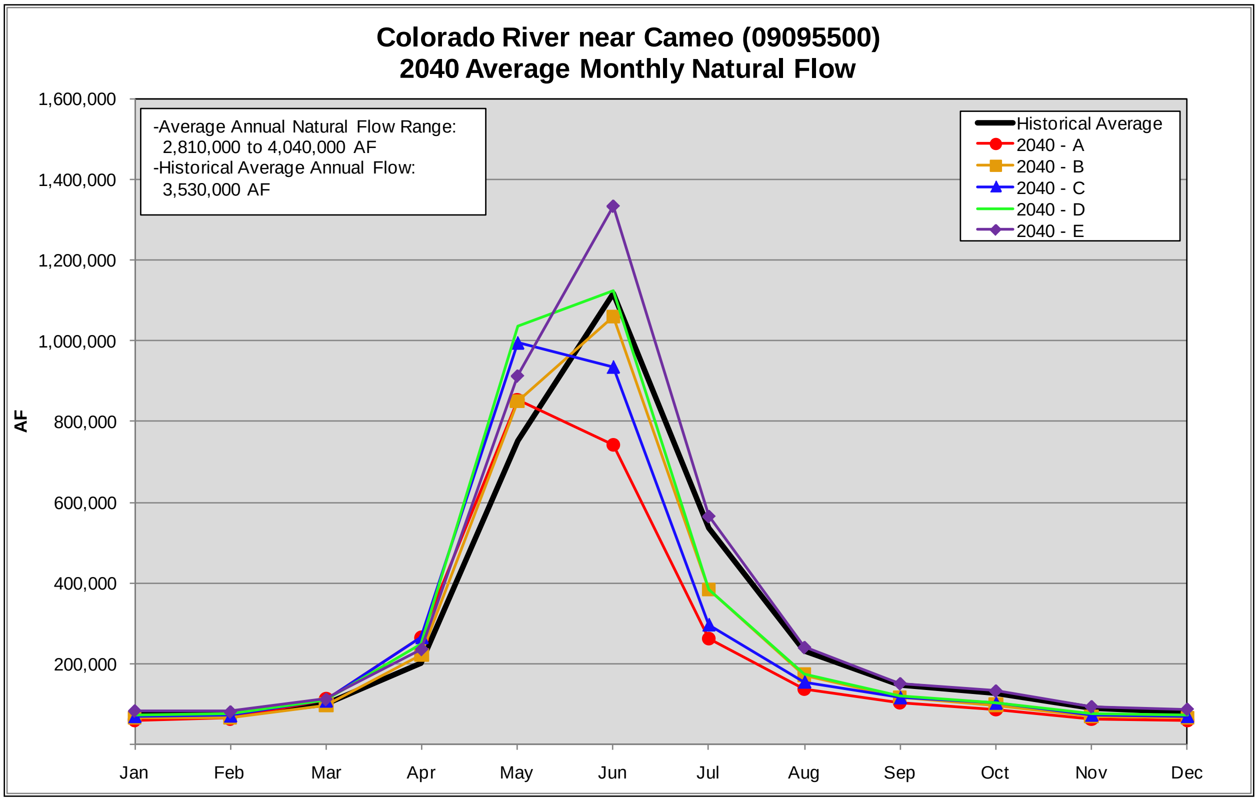


Figure 3-13 – Colorado River near Cameo - 2040 Average Monthly Natural Flow

Natural flows associated with the five climate projections at the three locations presented indicate a shift towards more river flow in April and May and generally less river flow in other months, compared to historical natural flows. This trend of increased projected natural flow in spring and early summer months, and less flow in late summer, fall and winter months, is seen in most locations throughout the Study Area, as shown in the figures presented in Appendix C for the 2040 climate projections. Throughout the Study Area, projections generally show a shift toward earlier runoff for 2040. On average projected 2040 runoff shifts earlier by 8 days.

In addition to the figures showing seasonal differences between historical natural flow and climate projected natural flow, Appendix C also includes tables summarizing the monthly and annual differences for the 2040 projections. Information in the tables includes average monthly and average annual natural flow for each of the five projections, and the annual volume reduction and percent reduction from historical.

Figure 3-14 shows low-flow information at the Gunnison River near Gunnison gage location. Three low-flow statistics are provided in Figure 3-14. General descriptions for the components of the low-flow comparison charts are provided in Section 3.1. Low-flow comparison graphs for the selected locations are included in Appendix C for the 2040 and climate projections.

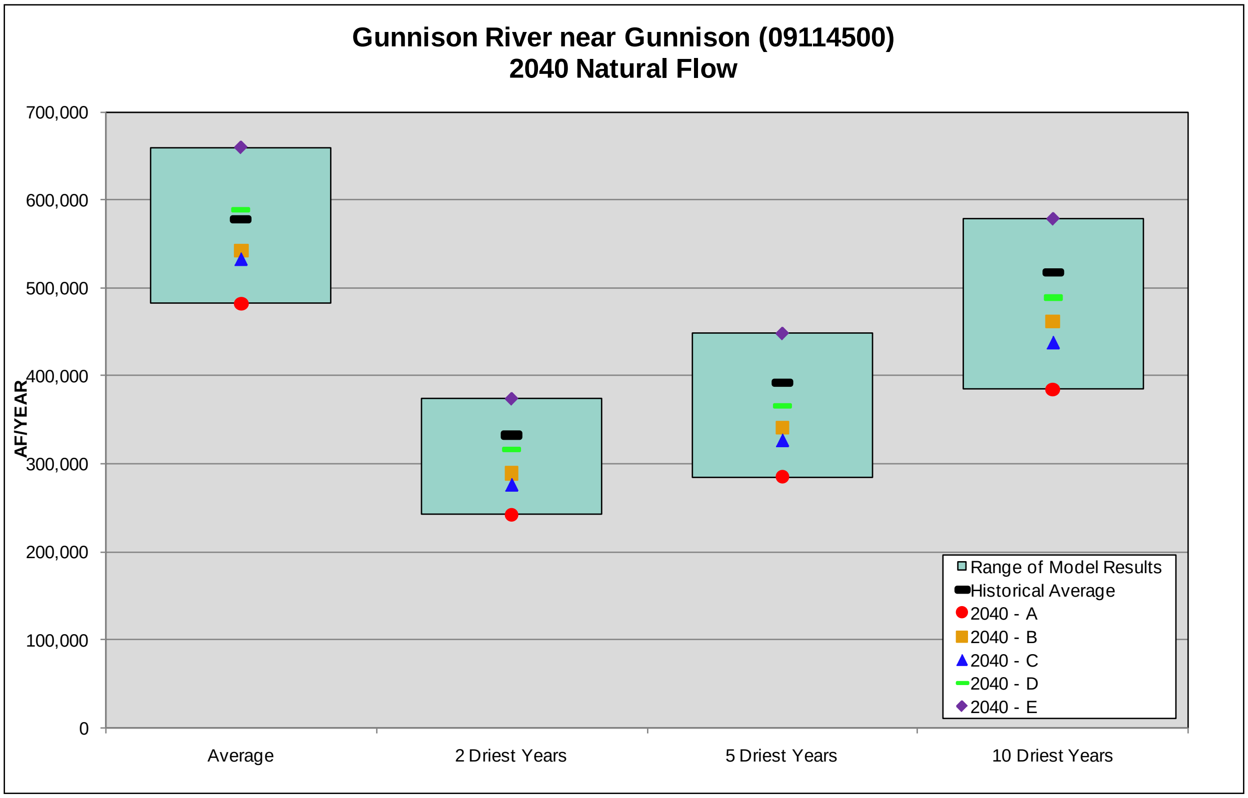


Figure 3-14 – Gunnison River near Gunnison - 2040 Natural Flow Low-Flow Comparison

The 2040 tables (Tables C1 through C5 in Appendix C) summarizing monthly and annual differences and the 2040 low-flow comparison charts show the following:

- Most locations reviewed in the Study Area show less average annual natural flow compared to historical natural flow for three of the five projections (2040-A, 2040-B, and 2040-C).
- Locations included in Appendix C throughout the Study Area show more average annual natural flow for the 2040-E climate projection compared to historical natural flow.
- The historical annual flow values generally fall within the projected ranges for the 2040 climate projections throughout the Study Area.
- The range of projected annual lows for the 2040 climate tends to be greater for locations in the southern portion of the Study Area.

2070 Natural Flow

Figure 3-15 shows the seasonal variation in natural flow at the Colorado River near Cameo gage over the 1950 through 2005 study period for the historical model, and for natural flows adjusted for the 2070 climate projections. All of the climate projections show a clear shift toward earlier runoff, as shown in Figure 3-15. Each of the projections show decreased natural flow at the Colorado River near Cameo gage in the summer and fall months. Throughout the Study Area, all of the projections generally show a shift toward earlier runoff for 2070 and on average projected 2070 runoff shifts earlier by 14 days.

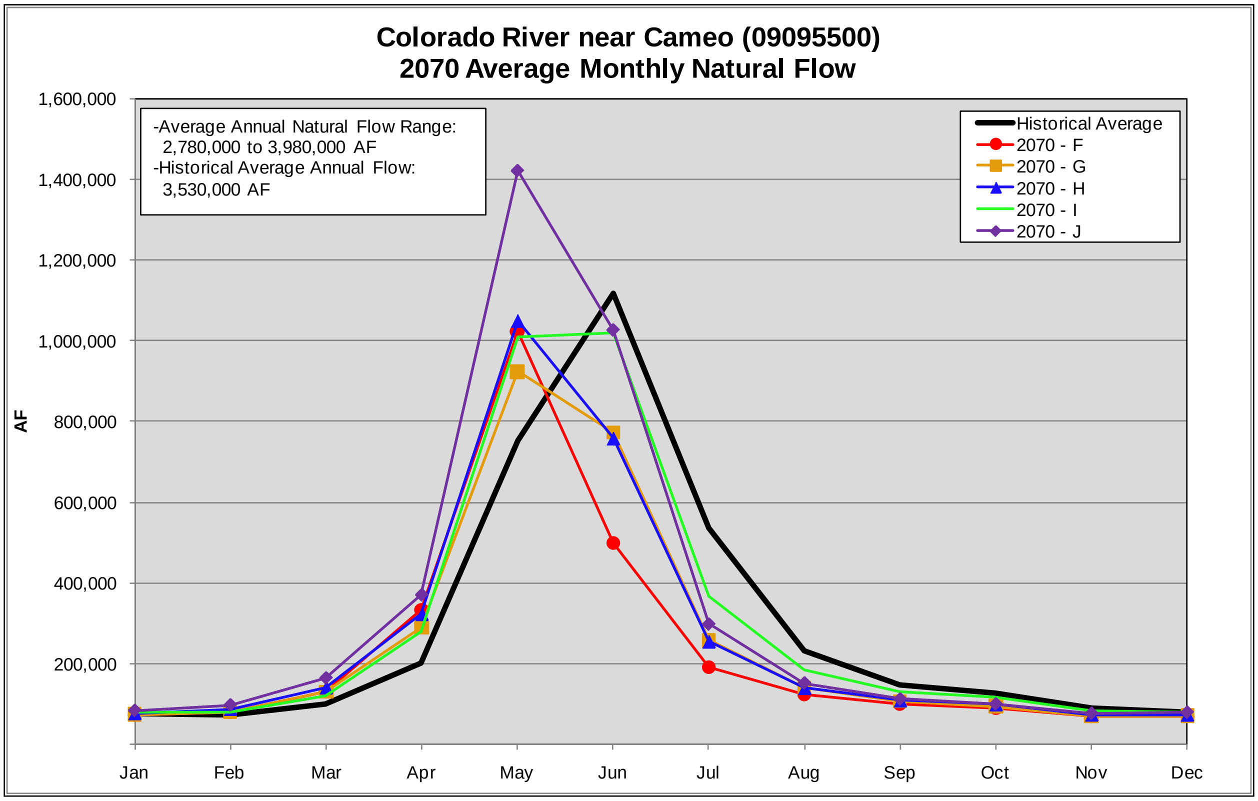


Figure 3-15 – Colorado River near Cameo - 2070 Average Monthly Natural Flow

In addition to the figures showing seasonal differences between historical natural flow and climate projected natural flow, Appendix C also includes tables summarizing the monthly and annual differences for the 2070 projections. Information in the tables includes average monthly and average annual natural flow for each of the five projections, and the annual volume reduction and percent reduction from historical. Low-flow comparison graphs for the selected locations are included in Appendix C for the 2070 climate projections.

The Appendix C graphs and 2070 tables (Tables C6 through C10) summarizing monthly and annual differences show the following:

- Locations in the northern portion of the Study Area show increases in climate projected natural flow compared to historical natural flow for some of the climate projections.

- Many locations in the southern portion of the Study Area show decreases in natural flow compared to historical natural flow for each of the 2070 climate projections (Los Pinos at La Boca, Florida River at Bondad, Animas River near Cedar Hill, La Plata River at the Stateline, Mancos River near Towaoc, Dolores River near Bedrock, and San Miguel River at Naturita).

- The historical annual natural flow generally falls within the low-flow statistic ranges for the 2070 climate projections in the Yampa, White, and Colorado basins. However, the low-flow ranges for the climate projections are lower than historical annual low-flow values for most locations in the Gunnison basin and the southwestern portion of the Study Area.

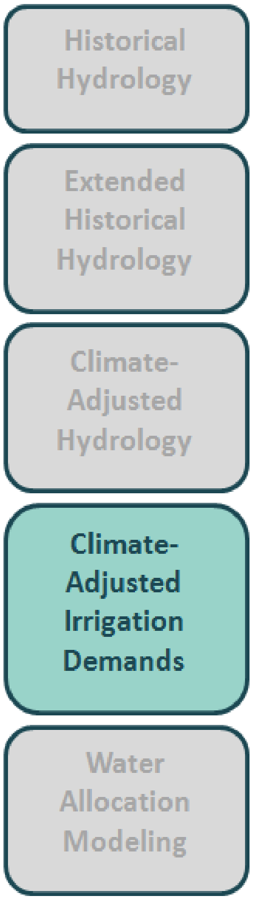
- The range of annual low-flow statistic values in the northern portion of the Study Area is wider between the five individual 2070 climate projections than between the five individual 2040 climate projections. However, the range of annual low-flow values in the central and southern portion of the Study Area is narrower between the five individual 2070 climate projections than between the five individual 2040 climate projections.

The climate-adjusted natural flows were re-sequenced as described in Sections 2.3.3 and 2.3.4 and the ensemble of re-sequenced, climate-adjusted flows was analyzed to determine the frequency and intensity of spells given the impact of projected climate change. The results of those spell analyses for selected gage locations are provided in Appendix C, Tables C11 through C54.

Where to find more detailed information:

Natural flow based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for the 227 locations represented in the CRWAS modeling effort through the CRWAS Data Viewer (http://cdss.state.co.us/).

3.5 Climate-Adjusted Irrigation Demands



This section presents the results of model analyses using the CDSS StateCU and StateMod models described in Section 2.3.1. The results presented here are based on the 56-year-long record of historical hydrology and 56-year-long records of climate-adjusted hydrology. The results from the model analyses using the 100-member ensembles of the alternate historical hydrology and the alternate hydrology of climate change can be obtained through the CRWAS Data Viewer available via the CWCB website (http://cwcb.state.co.us). Those results can be used to evaluate the reliability of water rights and infrastructure assuming current levels of irrigated acreage, M&I demands, and reservoir operations.

3.5.1 *Climate-Adjusted CIR*

CIR were estimated using the monthly Blaney-Criddle methods in StateCU, as discussed in Section 2.3.5. The Blaney-Criddle method relies on mean monthly temperature to both define the growing season, and in the monthly equation to determine potential crop consumptive use. Therefore, as temperature increases, potential crop consumptive use increases. As discussed in Section 2.3.5, Blaney-Criddle is an appropriate method for determining crop demand for climate projections because the global climate model archives provide monthly mean temperature and monthly total precipitation values.

Crop irrigation water requirement is determined by subtracting the amount of monthly precipitation estimated to be effective in directly meeting crop demands from potential crop consumptive use. Therefore, as irrigation season precipitation increases, CIR decreases.

2040 CIR at Climate Stations

Table 3-9 presents the increased annual pasture grass CIR compared to historical for each of the 2040 climate projection scenarios at selected climate stations based on the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent a range of elevations and locations of irrigated acreage in the Study Area.
Table 3-10 presents the increase in growing season days for pasture grass at the selected climate stations compared to historical for each of the 2040 climate projection scenarios.

Table 3-9 – 2040 Increase in Average Annual Pasture Grass CIR Compared to Historical

Climate Station	Historical CIR (inches)	Increase In CIR (inches) for Climate Projections					
		2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave
Fruita 1W	30.3	9.2	5.4	8.6	5.7	2.9	6.3
Glenwood Springs 2	22.9	8.8	5.3	7.5	5.6	2.1	5.8
Grand Lake 6SSW	22.3	5.9	3.3	4.5	4.0	0.9	3.7
Rangely 1E	27.2	8.9	5.0	8.2	5.3	2.6	6.0
Meeker 3W	19.4	8.2	4.7	7.1	4.9	2.1	5.4
Maybell	19.9	7.8	4.3	7.2	4.7	2.2	5.2
Hayden	19.3	8.0	4.2	6.7	4.7	1.9	5.1
Yampa	24.4	5.2	3.2	3.9	3.4	1.0	3.4
Delta 3E	30.3	9.4	5.6	8.4	5.9	2.7	6.4
Montrose No 2	27.7	9.4	5.7	8.2	5.9	2.6	6.4
Gunnison 3SW	29.0	5.1	3.8	4.4	4.0	1.4	3.7
Cortez	25.8	9.0	5.8	7.8	5.6	2.8	6.2
Durango	27.9	4.1	3.4	3.2	2.5	0.9	2.8
Norwood	28.2	4.0	3.2	3.2	2.6	0.9	2.8
Average[1]	25.3	7.4	4.5	6.4	4.6	1.9	4.9

1) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Table 3-10 – 2040 Increase in Average Pasture Grass Growing Season Compared to Historical

Climate Station	Average Historical Growing Season (Days)	Average Increase in Growing Season (Days) for Climate Projections					
		2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave
Fruita 1W	217	33	14	24	14	8	19
Glenwood Springs 2	198	35	14	25	14	8	19
Grand Lake 6SSW	231	30	12	20	13	7	17
Rangely 1E	198	29	11	23	11	6	16
Meeker 3W	182	32	12	25	14	8	18
Maybell	173	28	11	23	13	7	17
Hayden	177	26	11	21	13	7	16
Yampa	170	26	11	21	15	8	16
Delta 3E	219	33	14	22	14	8	18
Montrose No 2	208	36	15	25	16	8	20
Gunnison 3SW	172	26	12	21	16	8	17
Cortez	203	42	15	26	19	9	22
Durango	215	40	16	24	18	8	21
Norwood	199	38	14	26	17	8	21
Average[1)]	197	32	13	23	15	8	18

1) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-16 spatially shows 2040 climate projections' combined average annual increase in CIR compared to historical average CIR, based on the 54 climate stations used in the CDSS modeling over the 1950 through 2005 study period. The Study Area combined average CIR for the five projections shows an increase of 4.9 inches over historical average pasture grass CIR and 18 additional growing season days. The following general trends can be observed from Table 3-9, Table 3-10, and Figure 3-16:

- Basin-wide average CIR increases from 1.9 to 7.4 inches as shown in Table 3-9.

- There is an increase in CIR for each of the climate projections at locations throughout the Study Area. The 2040-A and 2040-D scenarios show the greatest increase from historical; whereas the 2040-E shows the least increase from historical.

- Increases in CIR throughout the Study Area are primarily due to higher temperature, which increases: 1) the number of days in the growing season for perennial crops such as pasture grass, alfalfa, and orchards and 2) the crop demand for irrigation water. In addition, as noted in the previous section, precipitation is generally less during the growing season, decreasing the amount of crop demand satisfied from effective precipitation; thereby increasing the crop demand for irrigation water.

- Basin-wide average growing season days increase from 8 to 32 days.

- The 2040 climate projections' combined result in an average increase in growing season days for pasture grass ranging from 17 days at higher elevations to 22 days at the Cortez climate station.

- The increase in CIR is greater at lower elevation stations including Fruita, Delta, Montrose, and Cortez.

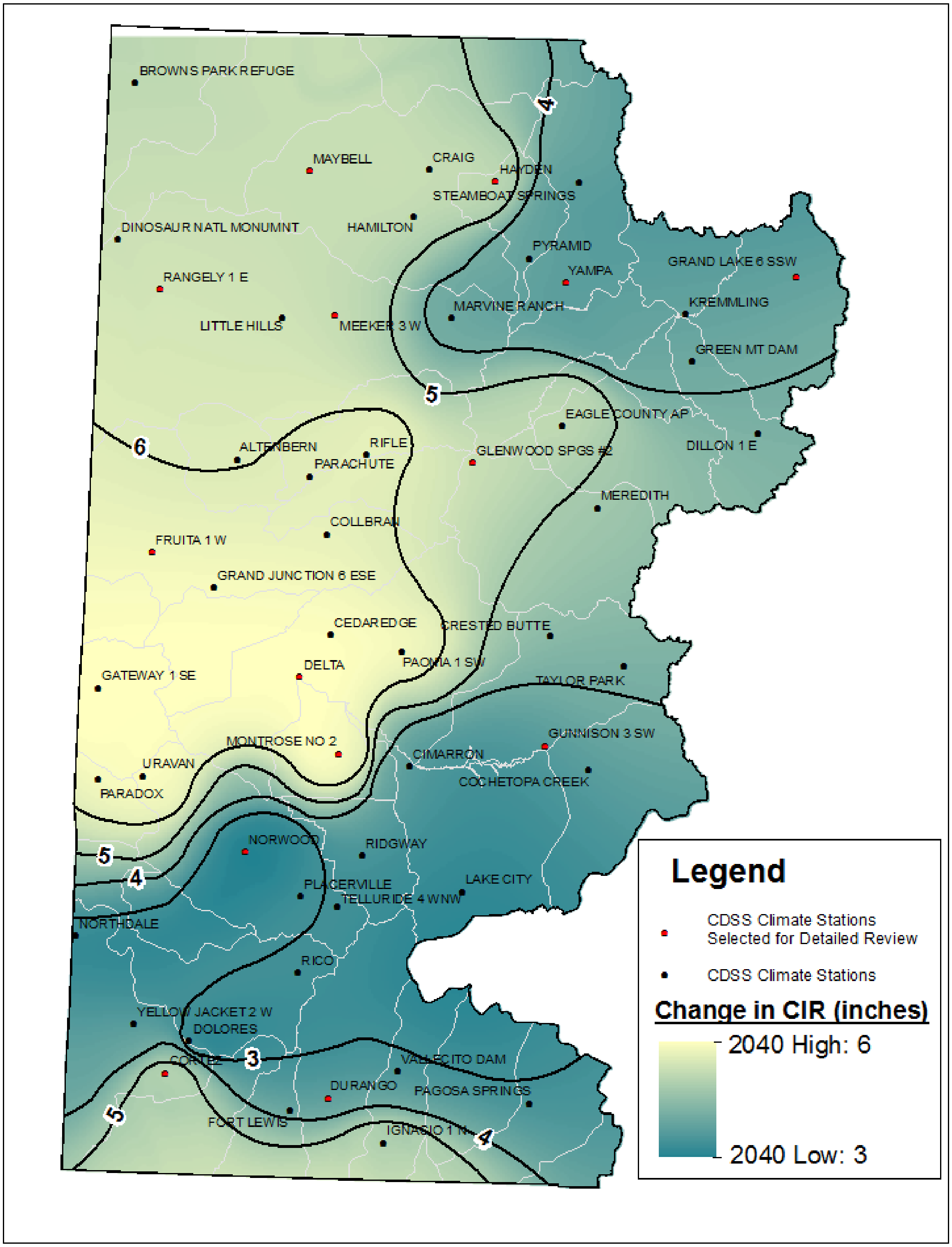


Figure 3-16 – 2040 Projections' Combined Increase in Pasture Grass CIR from Historical CIR (inches)

Figure 3-17 shows the average monthly pasture grass CIR at the Delta climate station for each of the 2040 climate projections compared to the historical average monthly CIR for the 1950 through 2005 study period. Similar graphs are included in Appendix D for each selected climate station for the 2040 projections. As with Figure 3-17, the figures shown in Appendix D generally show that peak CIR continues to be in the same month as occurred historically (July in most locations throughout the Study Area) except as noted below.

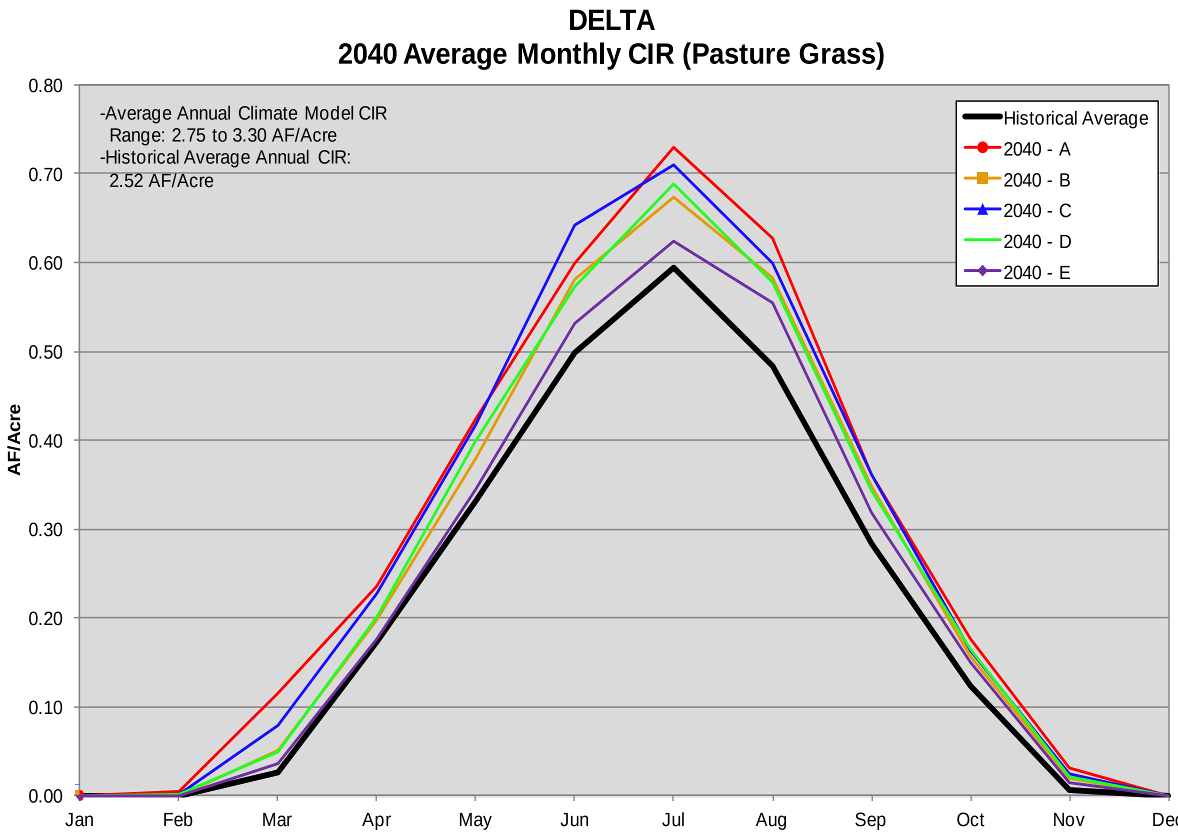


Figure 3-17 – Delta 2040 Average Monthly CIR Comparison

Figure 3-18 shows the average monthly pasture grass CIR at the Gunnison climate station for each of the 2040 climate projects compared to the historical average monthly CIR for the 1950 through 2005 study period. Similar to the Gunnison climate station, the figures for the higher elevation stations including Grand Lake, Yampa, Durango, and Norwood, included in Appendix D, show both the peak historical and climate projected CIR occurring in June.

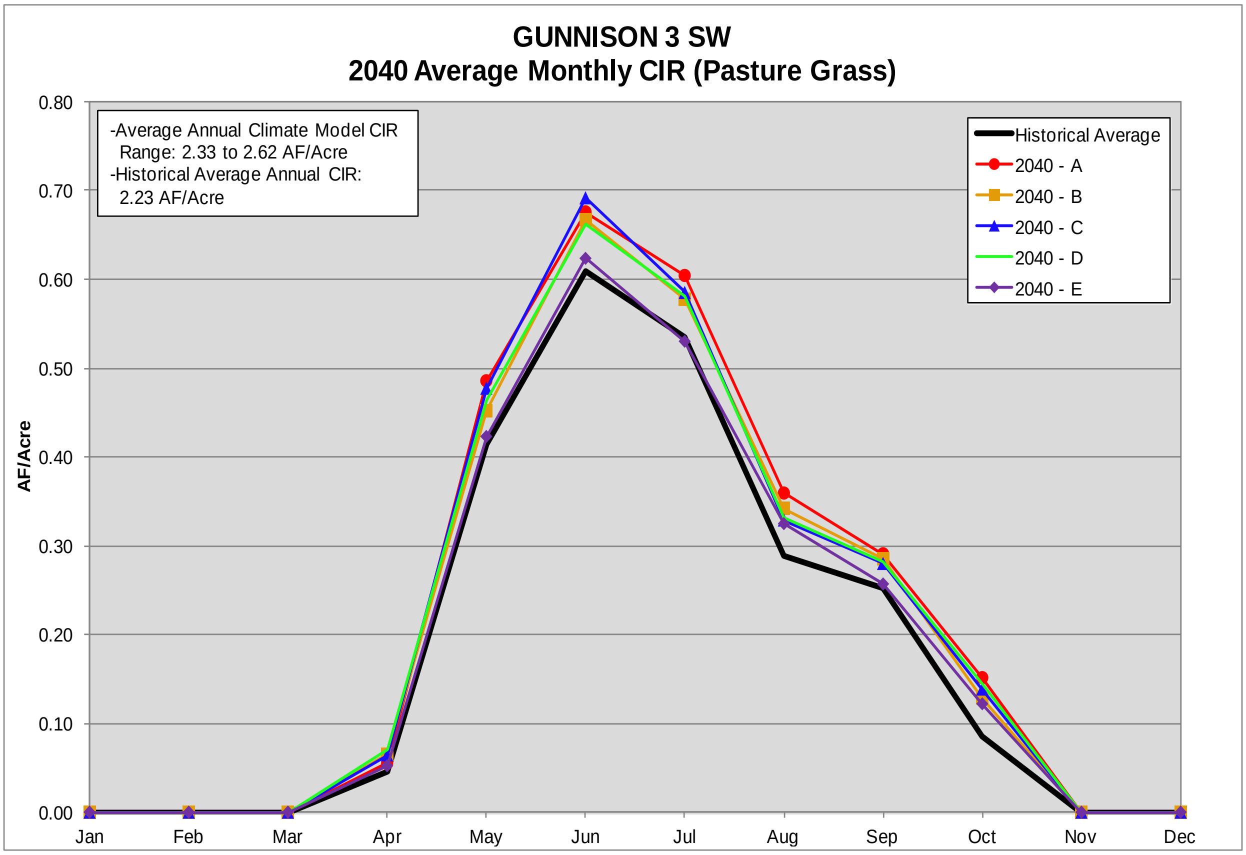


Figure 3-18 – Gunnison 2040 Average Monthly CIR Comparison

2070 CIR at Climate Stations

Table 3-11 presents the increased annual pasture grass CIR compared to historical for each of the 2070 climate projection scenarios at selected climate stations based on the 1950 through 2005 study period. The representative climate stations are the same selected in Table 3-3 to represent a range of elevations and locations of irrigated acreage in the Study Area.
Table 3-12 presents the increase in growing season days for pasture grass at the selected climate stations compared to historical for each of the 2070 climate projection scenarios.

Table 3-11 – 2070 Increase in Average Annual Pasture Grass CIR Compared to Historical

Climate Station	Historical CIR (inches)	Increase In CIR (inches) for Climate Projections					
		2070-F	2070-G	2070-H	2070-I	2070-J	Comb. Ave
Fruita 1W	30.3	15.3	10.2	10.3	7.1	11.0	10.8
Glenwood Springs 2	22.9	13.3	9.7	9.4	5.7	9.8	9.6
Grand Lake 6SSW	22.3	6.7	6.3	5.9	2.8	5.8	5.5
Rangely 1E	27.2	14.5	9.4	9.5	6.4	9.5	9.9
Meeker 3W	19.4	12.8	8.4	8.6	5.4	8.3	8.7
Maybell	19.9	12.5	8.1	8.3	5.3	7.9	8.4
Hayden	19.3	11.4	8.3	8.2	4.6	7.4	8.0
Yampa	24.4	5.9	5.0	4.9	2.8	4.5	4.6
Delta 3E	30.3	15.0	10.8	10.6	7.1	11.4	11.0
Montrose No 2	27.7	14.6	10.7	10.4	7.0	11.2	10.8
Gunnison 3SW	29.0	6.8	5.8	5.6	3.7	6.3	5.7
Cortez	25.8	13.6	10.5	10.3	7.7	11.3	10.7
Durango	27.9	5.3	4.2	4.0	3.2	4.9	4.3
Norwood	28.2	5.5	3.7	3.7	3.1	4.7	4.1
Average[1)]	25.3	10.9	7.9	7.8	5.1	8.1	8.0

1) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Table 3-12 – 2070 Increase in Average Growing Season for Pasture Grass Compared to Historical

Climate Station	Average Historical Growing Season (Days)	Average Increase in Growing Season (Days) for Climate Projections					
		2070-F	2070-G	2070-H	2070-I	2070-J	Comb . Ave
Fruita 1W	217	47	36	35	20	35	35
Glenwood Springs 2	198	46	39	35	22	32	35
Grand Lake 6SSW	231	43	36	36	17	37	34
Rangely 1E	198	42	34	31	18	28	31
Meeker 3W	182	50	37	36	21	30	35
Maybell	173	46	33	33	20	27	32
Hayden	177	42	33	32	20	26	31
Yampa	170	44	33	33	20	27	31
Delta 3E	219	44	36	34	19	33	33
Montrose No 2	208	46	38	35	22	34	35
Gunnison 3SW	172	42	33	33	21	28	32
Cortez	203	51	41	38	24	39	39
Durango	215	50	42	39	22	39	39
Norwood	199	50	40	38	23	36	37
Average[1)]	197	46	37	35	21	32	34

1) Average of the 14 stations presented compares closely with the average of the 52 stations used in the CDSS analysis.

Figure 3-19 spatially shows 2070 climate projections' combined average annual increase in CIR compared to historical average CIR, based on the 54 climate stations used in the CDSS modeling over the 1950 through 2005 study period. The Study Area combined average CIR for the five projections shows an increase of 8.0 inches over historical average pasture grass CIR and 34 additional growing season days. The following general trends can be observed from Table 3-11, Table 3-12, and Figure 3-19 plus comparison to 2040 average annual increases:

- Basin-wide average CIR increases from 5.1 to 10.9 inches as shown in Table 3-11.
- There is an increase in CIR for each of the climate projections at locations throughout the Study Area. The 2070-F scenario shows the greatest increase from historical.
- As with the 2040 climate projections, increases in CIR throughout the Study Area are primarily due to higher temperature, which increases: 1) the number of days in the growing season for perennial crops such as pasture grass, alfalfa, and orchards and 2) the crop demand for irrigation water. In addition, as noted in the previous section, precipitation is generally less during the growing season, decreasing the amount of crop demand satisfied from effective precipitation; thereby increasing the crop demand for irrigation water.
- Basin-wide average growing season days increase from 21 to 46 days.
- The increase in CIR is greater at lower elevation stations including Fruita, Delta, Montrose, and Cortez. Figure 3-19 highlights the greater increase in annual CIR at lower compared to higher elevations.

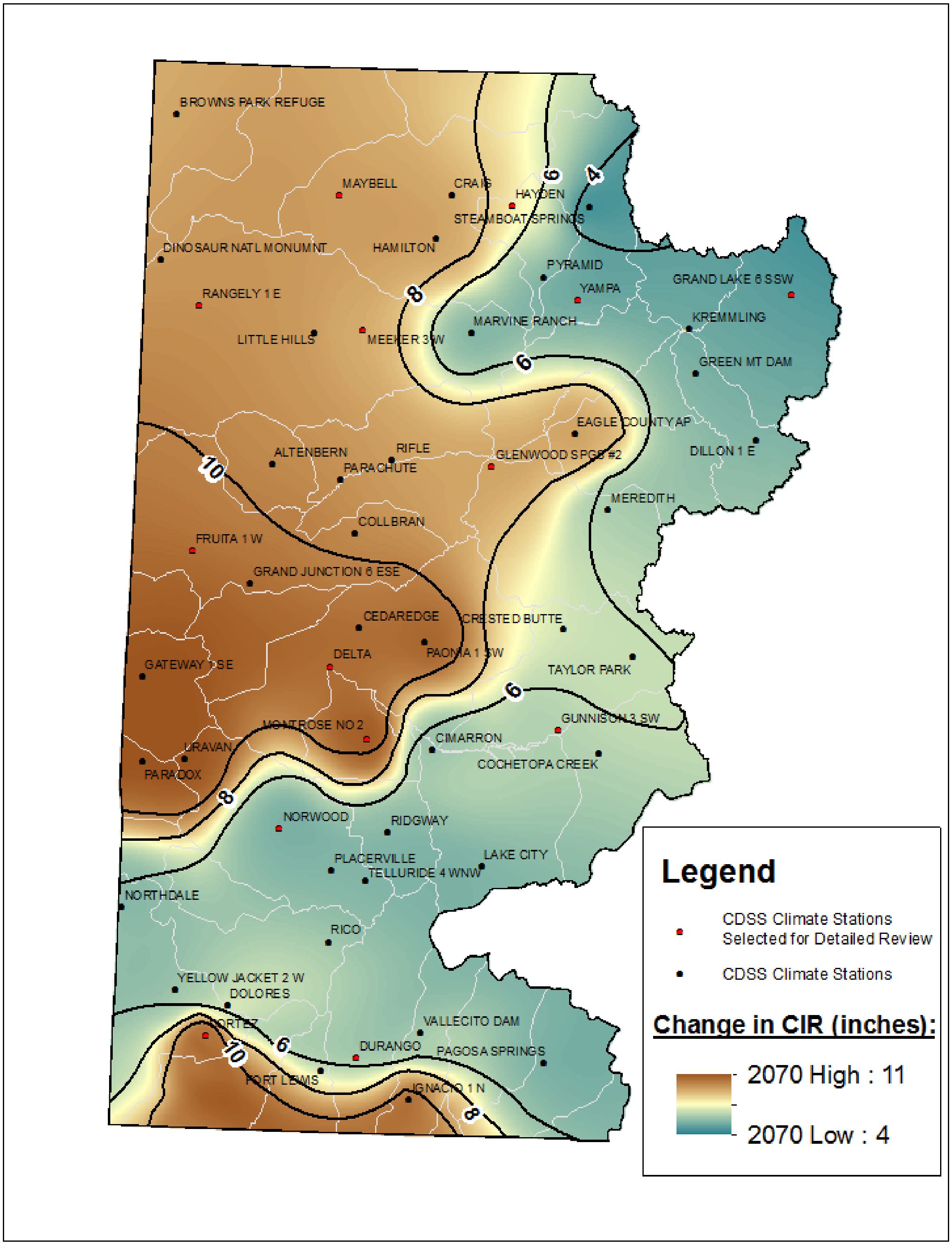


Figure 3-19– 2070 Projections' Combined Increase in Pasture Grass CIR from Historical CIR (inches)

Appendix D includes graphs showing 2070 projected average annual CIR each climate station, similar to the example 2040 graph presented in Figures 3-17 and 3-18. The figures shown for 2070 in Appendix D generally show that peak CIR continues to be in the same month as occurred historically.

As discussed in Section 2.3.6, the increase in CIR directly impacts irrigation diversion demands represented in the water resources planning models. The results shown have been summarized based on pasture grass, which represents about 80 percent of the irrigated acreage in the basin. Other perennial crops grown in the Study Area, including alfalfa and orchard, account for an additional 12 percent of the total irrigated acreage and show similar increases in growing season and CIR. The annual crops grown in the basin; mostly corn, small grains and dry beans, show an increase in CIR and the potential for an earlier planting date in both 2040 and 2070. However, the growing season for annual crops, which is based on maximum days to harvest, does not increase.

2040 CIR for Study Basins

Table 3-13 shows the average annual CIR for current irrigated acreage and crop types over the 1950 through 2005 study period, by Study Area basin, based on historical climate conditions and each 2040 projected climate scenario. The "Comb. Ave" column represents the projections combined average increase in CIR.

Table 3-13 – 2040 Average Annual Study Basin Increase in CIR Compared to Historical Conditions (AF)

Study Basin	Historical Basin CIR (AF)	Increase In CIR (AF) for Climate Projections						
		2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave	Comb. % Increase
Yampa	214,271	49,167	28,590	39,353	30,188	11,169	31,693	15%
White	45,903	16,244	9,678	13,893	9,903	4,188	10,781	23%
Upper Colorado	594,479	160,014	98,482	141,902	105,910	42,411	109,744	18%
Gunnison	618,147	150,305	100,427	134,421	103,215	42,068	106,087	17%
San Juan/Dolores	555,071	130,818	97,578	113,014	85,180	37,104	92,739	17%
Total	**2,027,872**	**506,549**	**334,754**	**442,584**	**334,396**	**136,940**	**351,045**	**17%**

The following can be observed based on Table 3-13:

- The 2040-A and 2040-C climate projections show the largest increase in basin CIR. This corresponds to these projections showing the greatest increase in average annual temperature throughout the Study Area.

- The 2040-E climate projection shows the smallest increase in basin CIR. This is a clear result of that projection having the lowest increase in average annual temperature values and an increase in irrigation season precipitation values throughout the Study Area.

- The largest percent increase in CIR from historical occurs in the White River basin for every climate projection, largely because the majority of irrigated acreage in the Basin is at a lower elevation where there is a more significant increase in temperature.

- The smallest percent increase in CIR from historical occurs in the Yampa River basin for every climate projection, largely because there is less temperature increase and there is a smaller decrease in irrigation season precipitation in the Yampa River basin compared to more southern portions of the Study Area.

2070 CIR for Study Basins

Table 3-14 shows the average annual CIR for current irrigated acreage and crop types over the 1950 through 2005 study period, by Study Area basin, based on historical climate conditions and each 2070 projected climate scenario. The “Comb. Ave” column represents the projections combined average increase in CIR.

Table 3-14 – 2070 Average Annual Study Basin Increase in CIR Compared to Historical Conditions (AF)

Study Basin	Historical Basin CIR (AF)	Increase In CIR (AF) for Climate Projections						
		2040-F	2040-G	2040-H	2040-I	2040-J	Comb. Ave	Comb. % Increase
Yampa	214,271	64,239	46,924	47,124	27,397	42,925	45,722	21%
White	45,903	24,387	16,128	16,469	10,623	16,255	16,772	37%
Upper Colorado	594,479	240,217	172,610	172,216	110,057	181,005	175,221	29%
Gunnison	618,147	224,742	168,355	165,999	111,986	183,659	170,948	28%
San Juan/Dolores	555,071	192,435	146,754	144,565	108,715	164,065	151,307	27%
Total	**2,027,872**	**746,019**	**550,770**	**546,373**	**368,778**	**587,910**	**559,970**	**28%**

The following can be observed based on Table 3-14:

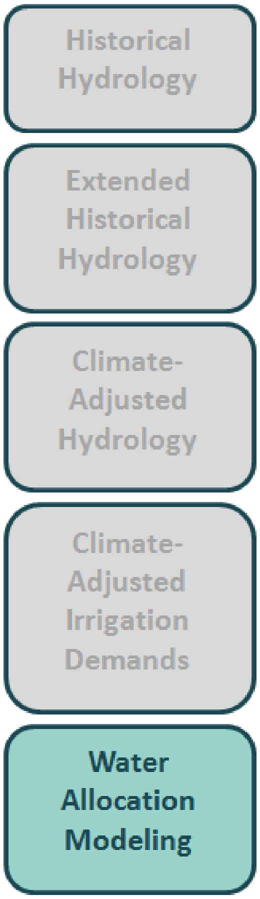
- The 2070-F climate projection shows the largest increase in basin CIR. This corresponds to the 2070-F projection showing the greatest increase in average annual temperature throughout the Study Area.

- The 2070-I projection shows the smallest percent increase in basin CIR. This is a clear result of that projection having the lowest increase in average annual temperature values throughout the Study Area and a slight increase in irrigation season precipitation for many areas in the Study Area.

- Similar to 2040, the largest percent increase in CIR from historical occurs in the White River basin for every climate projection, largely because the majority of irrigated acreage is lower in the White River basin where there is a more significant increase in temperature.

- Similar to 2040, the smallest percent increase in CIR from historical occurs in the Yampa River basin for every climate projection, largely because there is less temperature increase and there is a smaller decrease in irrigation season precipitation in the Yampa River basin more southern portions of the Study Area.

3.6 Water Allocation Modeling



3.6.1 *Modeled Streamflow*

StateMod distributes flow to meet demands based on the priorities of water rights and basin operations. During a particular time-step, modeled streamflow at any location represents natural flows less upstream depletions. The modeled streamflow includes flows available to meet future demands plus flow allocated by the model to downstream users. As discussed in Section 2.3.6, the allocation to downstream users can be limited by physical flow in the river, demands, water rights, and diversion capacities.

Modeled streamflow is estimated by StateMod for every location represented in the model. The full amount of modeled streamflow can be used at that location for non-consumptive uses (uses that will not divert or diminish flow required to meet downstream existing demands). A portion of the modeled streamflow may be available to meet future demands, as discussed in Section 3.6.1.

In addition, modeled streamflow is an indicator of the potential for exchange. An exchange requires water to be added to the river downstream in order for an equal amount of water to be taken at an upstream location, so as not to injure senior water right uses.

The 56-year record of climate-adjusted natural flows was used as input to the CDSS StateMod models. The results of those model runs serve as the basis for the results presented in this section. The ensemble of re-sequenced, climate adjusted flows was also used as input to the CDSS StateMod models and the results of those runs will provide information about the reliability of water rights and infrastructure in the face of droughts that are more severe than were experienced during historical period. The results of those runs are available through the CRWAS Data Viewer (http://cwcb.state.co.us/.)

2040 Modeled Streamflow

Figures 3-20 through 3-22 show the seasonal variation in modeled streamflow at three Colorado River stream gage locations from upper basin to lower basin (Colorado River Near Grand Lake, Colorado River at Dotsero, and Colorado River near Cameo) over the 1950 through 2005 study period for the historical model, and for the models representing demands and natural flows adjusted for the 2040 climate projections. As shown, some of the climate projections indicate a shift in modeled streamflow. For the higher elevation gage near Grand Lake, both the 2040-A and 2040-C projections show on average that peak runoff shifts in comparison to historical flows from June to May. As more tributaries join the Colorado River at Dotsero and Cameo, the shift in peak runoff is less pronounced downstream.

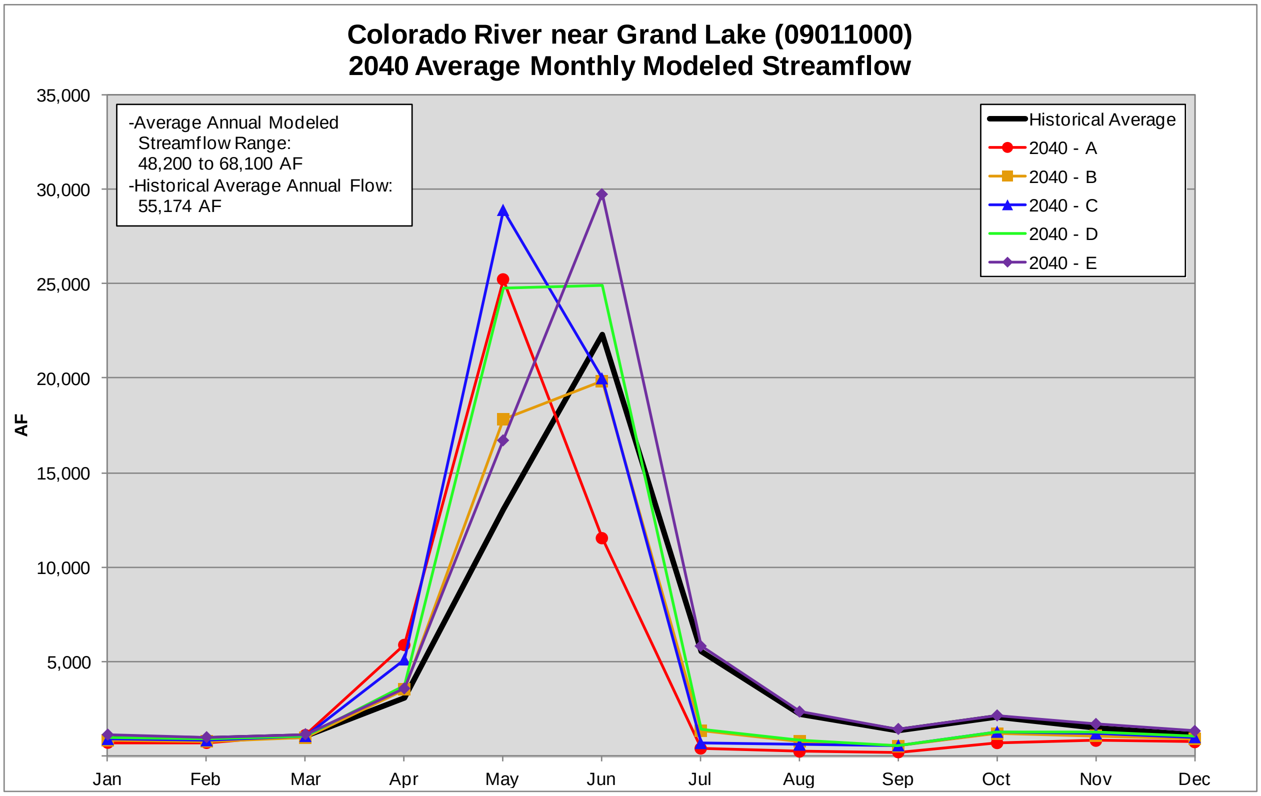


Figure 3-20 – Colorado River near Grand Lake - 2040 Average Monthly Modeled Streamflow

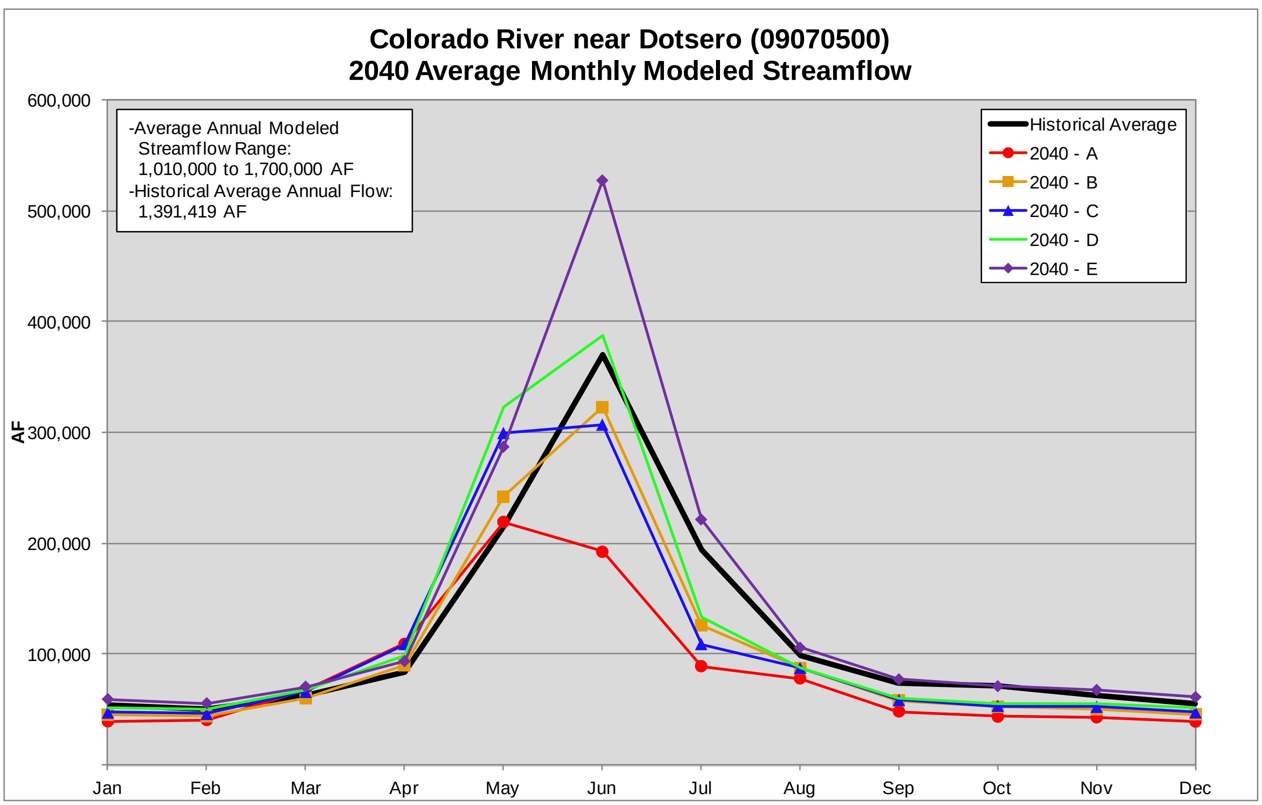


Figure 3-21 – Colorado River at Dotsero - 2040 Average Monthly Modeled Streamflow

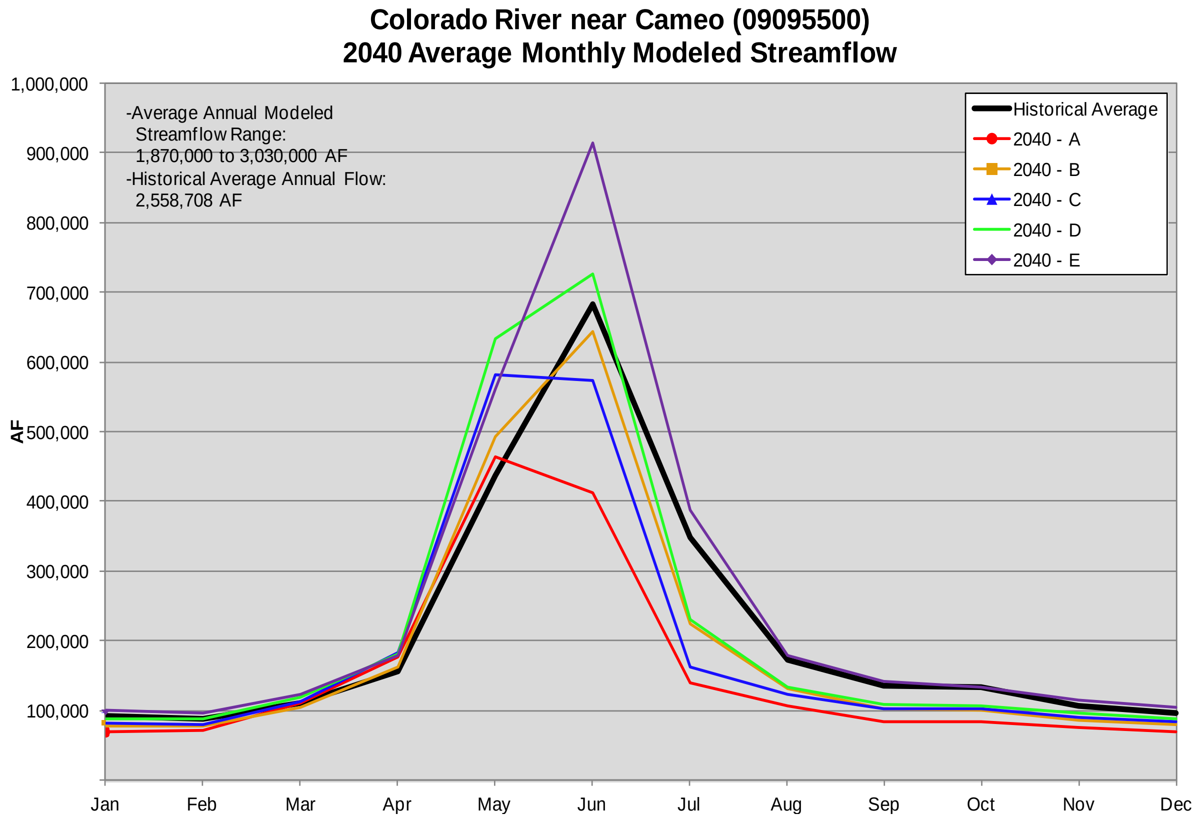


Figure 3-22 – Colorado River near Cameo - 2040 Average Monthly Modeled Streamflow

Similar to the climate projected natural flows discussed in Section 3.4.3, modeled streamflow at the three locations presented indicate more river flow in April and May and generally less river flow in other months, compared to historical streamflows. This trend of increased modeled streamflow in spring and early summer months, and less flow in late summer, fall and winter months, is seen in most locations throughout the Study Area, as shown in the figures presented in Appendix E for the 2040 climate projections. Modeled streamflow is an indicator of flow to meet non-consumptive demands and to maintain or improve riparian health. Higher peak runoff may be beneficial for riparian health; however lower flows in late summer and fall may impact non-consumptive needs.

Exceptions to the general pattern include stream flows below reservoirs that release based on flood control operations or to meet late season irrigation demands. On some tributaries, such as the Los Pinos River, flow is highly regulated by reservoirs for flood control and irrigation supplies. Flood release rules used in the basin model were provided for Vallecito Reservoir, in the upper Los Pinos River basin, by the reservoir operator. These operating rules, represented in the StateMod model using wet, dry, and average hydrologic year storage targets, were developed by the USBR based on current runoff patterns. As reflected on the downstream gage, Los Pinos River at La Boca shown in Figure 3-23 for 2040, releases are made in April to allow Vallecito Reservoir the capacity to store the runoff peak and avoid downstream flooding when the reservoir is forecast to fill (Historical, 2040-D and 2040-E simulations). The model operating rules do not consider the likelihood that the timing of releases would need to be revised as climate projections result in earlier runoff. Vallecito Reservoir operating rules also include drawing the reservoir down by the end of October to a level below the spillway gates, to avoid damage due to icing. This operation is clearly reflected in the downstream gage flow for the Historical and 2040-E projection simulations, as shown in Figure 3-23.

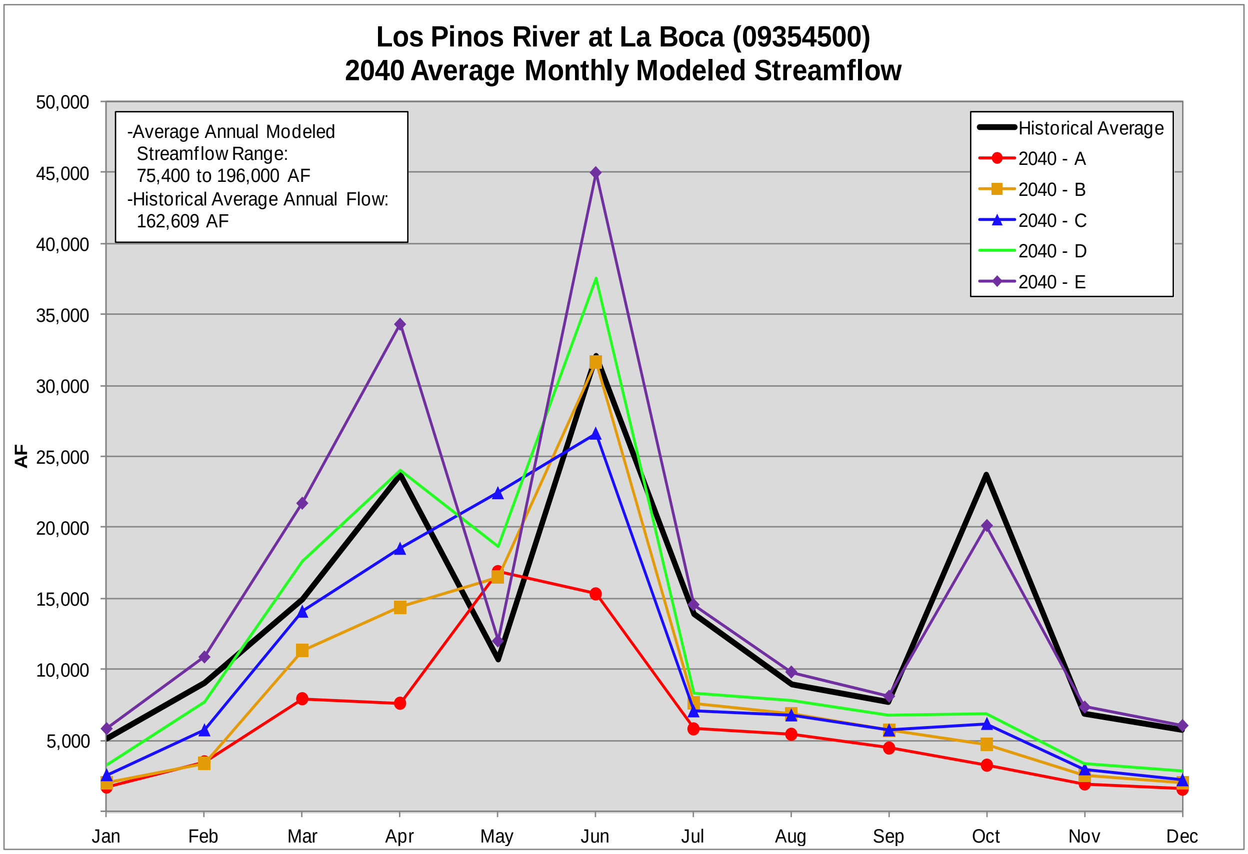


Figure 3-23 – Los Pinos at La Boca - 2040 Average Monthly Modeled Streamflow

In addition to the figures showing seasonal differences between historical modeled streamflow and climate projected streamflow, Appendix E also includes tables summarizing the monthly and annual differences for the 2040 projections. Information in the tables includes average monthly and average annual modeled streamflow for each of the five projections, and the annual volume reduction and percent reduction from historical. The 2040 tables (Tables E1 through E5) summarizing monthly and annual differences show the following:

- Most locations in the Study Area show less average annual modeled streamflow compared to modeled streamflow based on historical climate conditions for three of the five projections (2040-A, 2040-B, and 2040-C).

- Each location presented in Appendix E throughout the Study Area show more average annual modeled streamflow for the 2040-E climate projection compared to modeled streamflow based on historical climate conditions.

Figure 3-24 shows low-flow information at the Gunnison River near Gunnison gage location. Three low-flow statistics are provided in Figure 3-21. General descriptions for the components of the low-flow comparison charts are provided in Section 3.1.

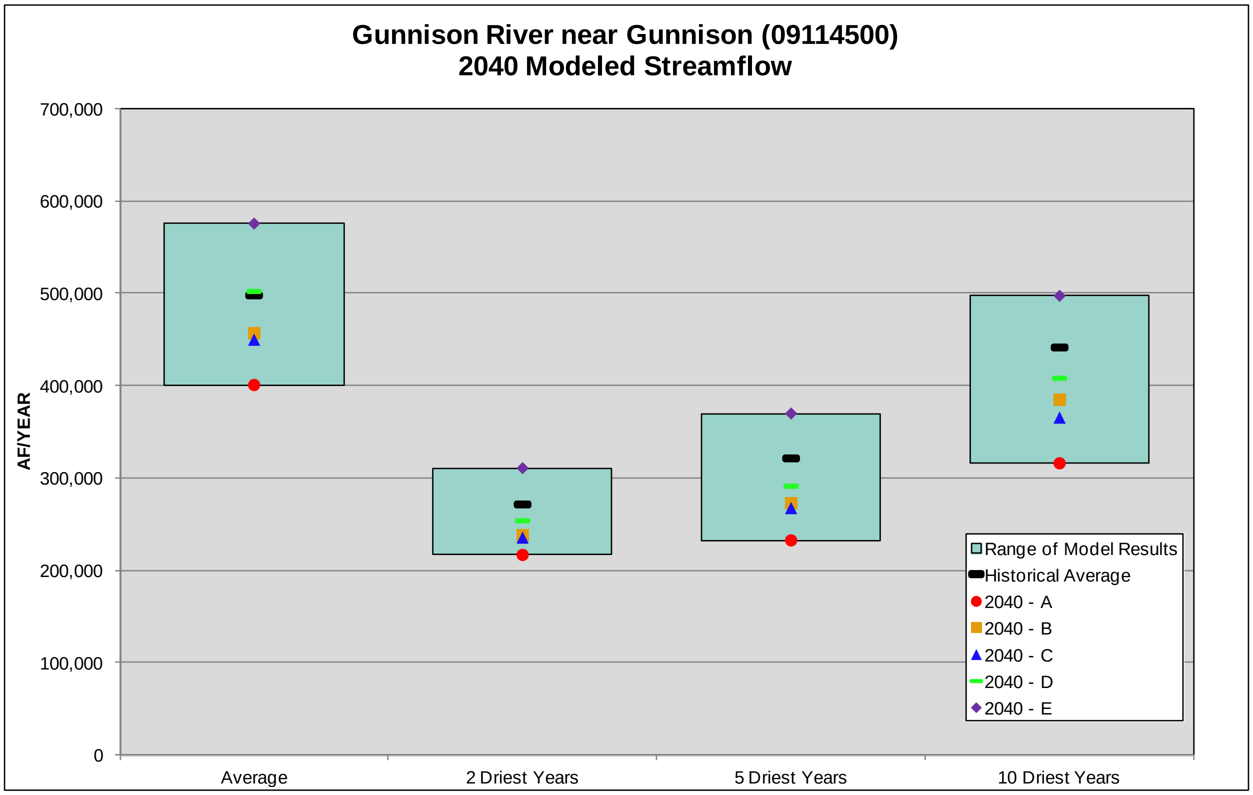


Figure 3-24 – Gunnison River near Gunnison - 2040 Modeled Streamflow Low-Flow Comparison

Low-flow comparison graphs for the selected locations are included in Appendix E for the 2040 climate projections. Similar to the comparison shown in Figure 3-24, the following general observations can be drawn from the 2040 low-flow comparison graphs:

- The historical annual low-flow values fall within the low-flow statistic ranges for the 2040 climate projections at locations throughout the Study Area.

- There is a wider range of annual low-flow statistic values for the 2040 climate projections for locations in the southern portion of the Study Area that may, in part, reflect limited ability of the climate models to reflect monsoon patterns.

2070 Modeled Streamflow

Figure 3-25 shows the seasonal variation in modeled streamflow at the Colorado River near Cameo gage over the 1950 through 2005 study period for the historical model, and for the models representing demands and natural flows adjusted for the 2070 climate projections. Four of the five climate projections show a shift in peak streamflow from June to May, as compared to shifts in just two climate projections for 2040, as shown in Figure 3-25. All of the projections show decreased streamflow at the Colorado River near Cameo gage in the summer and fall months.

This trend of increased modeled streamflow in spring and less flow during the summer and fall months is seen at locations throughout the Study Area, as shown in the figures presented in Appendix E for the 2070 climate projections. Modeled streamflow is an indicator of flow to meet non-consumptive demands and to maintain or improve riparian health. Higher peak runoff may be beneficial for riparian health; however lower flows in late summer and fall may impact non-consumptive needs.

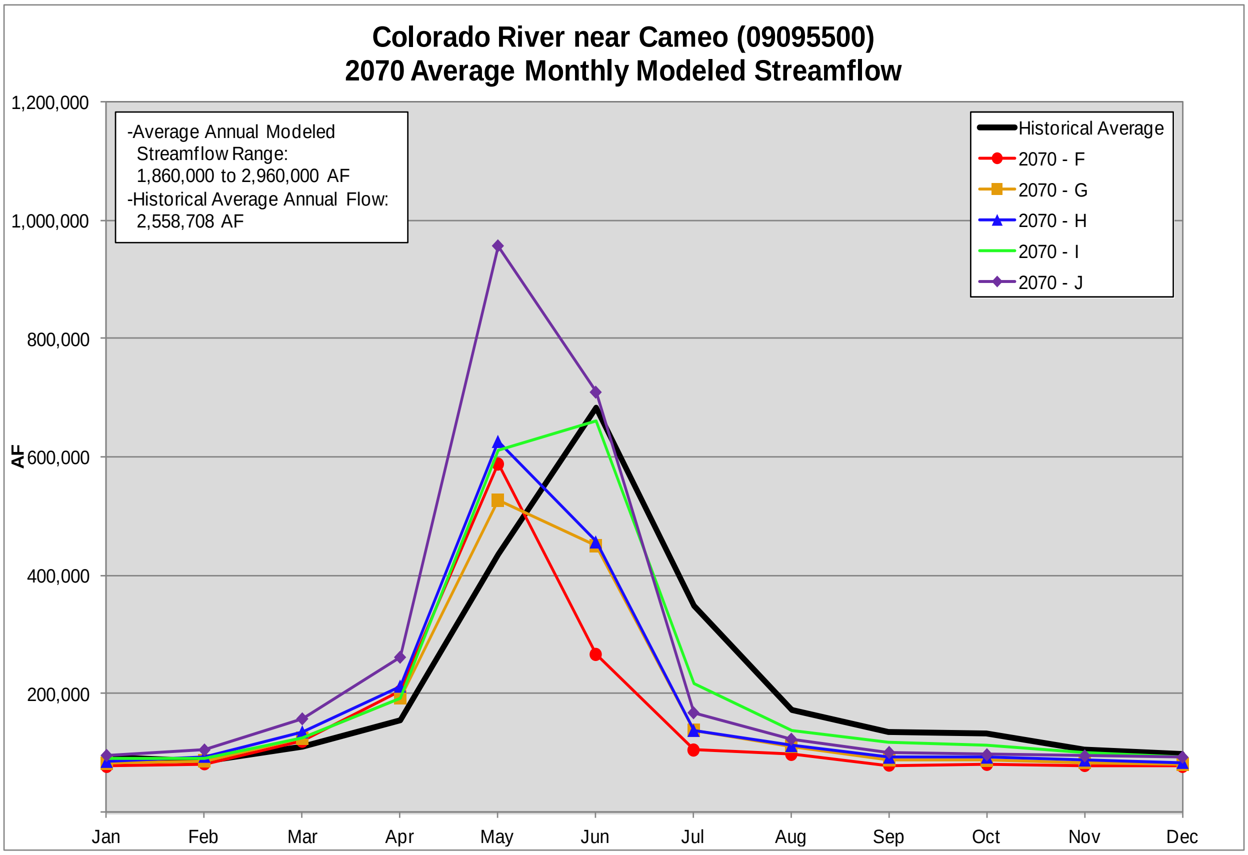


Figure 3-25 – Colorado River near Cameo - 2070 Average Monthly Modeled Streamflow

Exceptions include stream flows below reservoirs that release based on flood control operations or to meet late season irrigation demands. Figure 3-26 shows how releases in July for downstream use below Green Mountain Reservoir result in high July flow for some of the 2070 climate projections. Figure 3-27 however, shows that unlike the 2040 projections shown in Figure 3-23, further reduced inflow to Vallecito Reservoir does not “trigger” flood releases; therefore it follows a typical irrigation release pattern. Likewise, irrigation releases draw the reservoir down to the gate height and there is not a requirement for releases in October to avoid icing in any of the 2070 projections.

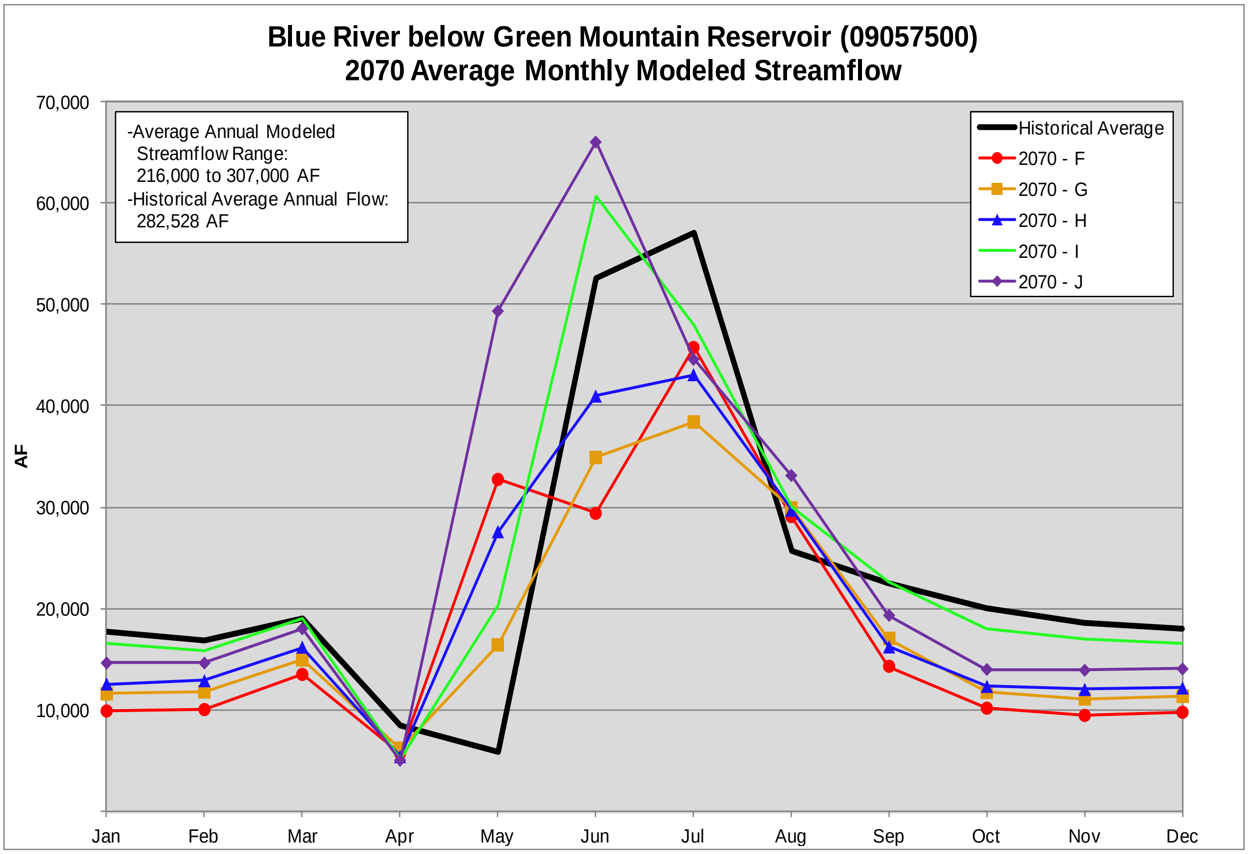


Figure 3-26 – Blue River below Green Mountain Reservoir - 2070 Average Monthly Modeled Streamflow

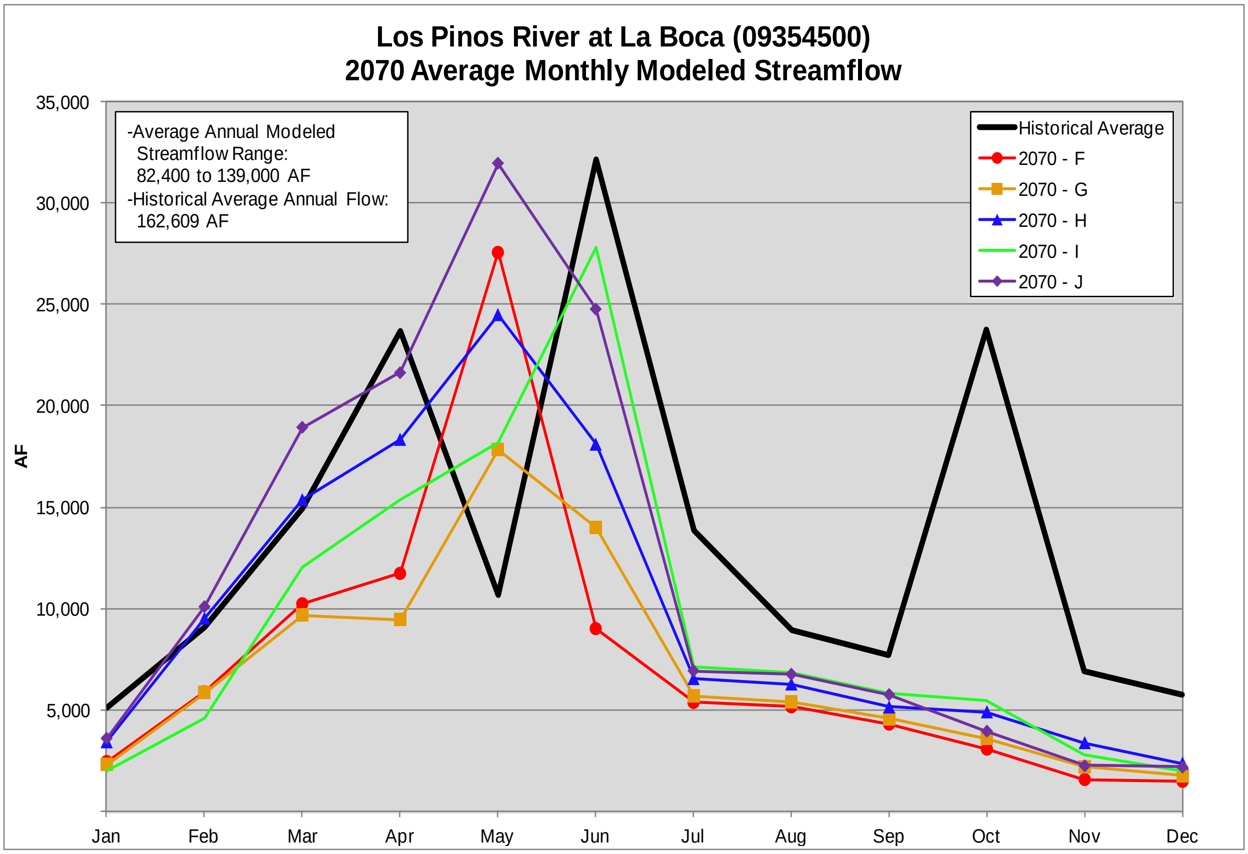


Figure 3-27 – Los Pinos River at La Boca - 2070 Average Monthly Modeled Streamflow

Appendix E also includes tables summarizing the monthly and annual differences for the 2070 projections. Information in the tables includes average monthly and average annual modeled streamflow for each of the five projections, and the annual volume reduction and percent reduction from historical. The 2070 tables (Tables E6 through E10) summarizing monthly and annual differences show the following:

- Locations in the northern portion of the Study Area and higher elevation locations in the upper Colorado basin (Colorado River nr Grand Lake and Roaring Fork River nr Aspen) show increases in average annual modeled streamflow compared to modeled streamflow based on historical climate conditions for some of the climate projections.

- Some locations in the southern and central portion of the Study Area do not show increases in average annual modeled streamflow compared to modeled streamflow for any of the climate projections.

- Some 2070 projections show greater average annual modeled streamflow compared to 2040 projections for locations throughout the Study Area.

Low-flow comparison graphs for the selected locations are included in Appendix E for the 2070 climate projections. The following general observations can be drawn from the 2070 low-flow comparison graphs:

- The historical annual modeled streamflow generally falls within the low-flow statistic ranges for the 2070 climate projections in the Yampa, White, and Colorado basins. However, the low-flow ranges for the climate projections are lower than historical annual low-flow values for most locations in the Gunnison basin and the southwestern portion of the Study Area.

- Annual low-flow statistic values in the northern portion of the Study Area show a wider range between the five individual 2070 climate projections than between the five individual 2040 climate projections. However, annual low-flow statistic values in the central and southern portion of the Study Area show a narrower range between the five individual 2070 climate projections than between the five individual 2040 climate projections.

Where to find more detailed information:

Modeled streamflow based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for locations represented in the CRWAS modeling effort through the CRWAS Data Viewer (http://cdss.state.co.us/).

3.6.2 *Water Available to Meet Future Demands*

StateMod distributes natural flow to meet demands based on the priorities of water rights and basin operations. During a particular time-step, water available to meet future demands at any location represents the portion of modeled streamflow that is not allocated to current downstream demands with existing water rights. The allocation to downstream users can be limited by physical flow in the river, demands, water rights, and diversion capacities. Water rights not serving current demands, including conditional rights, are not included in the Phase I model, nor does the StateMod model currently consider potential compact obligations. Therefore, water available to meet future demands includes water that may be used to satisfy future demands associated with existing absolute and conditional rights and future compact obligations.

Figure 3-28 and 3-29 show the seasonal variation in water available to meet future demands at two Colorado River stream gage locations (Colorado River near Grand Lake, and Colorado River near Dotsero) over the 1950 through 2005 study period for the historical model, and for the models representing demands and natural flows associated with the 2040 climate projections.

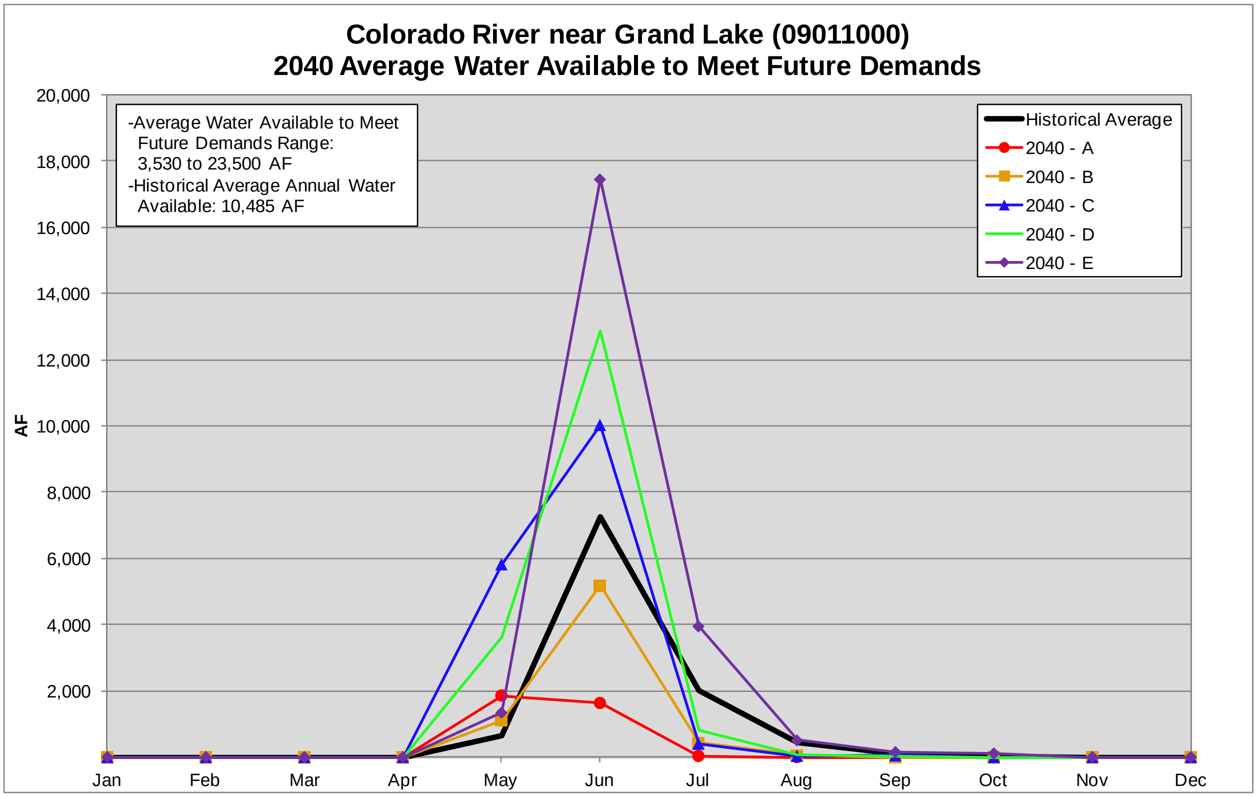


Figure 3-28 – Colorado River near Grand Lake - 2040 Average Monthly Water Available to Meet Future Demands

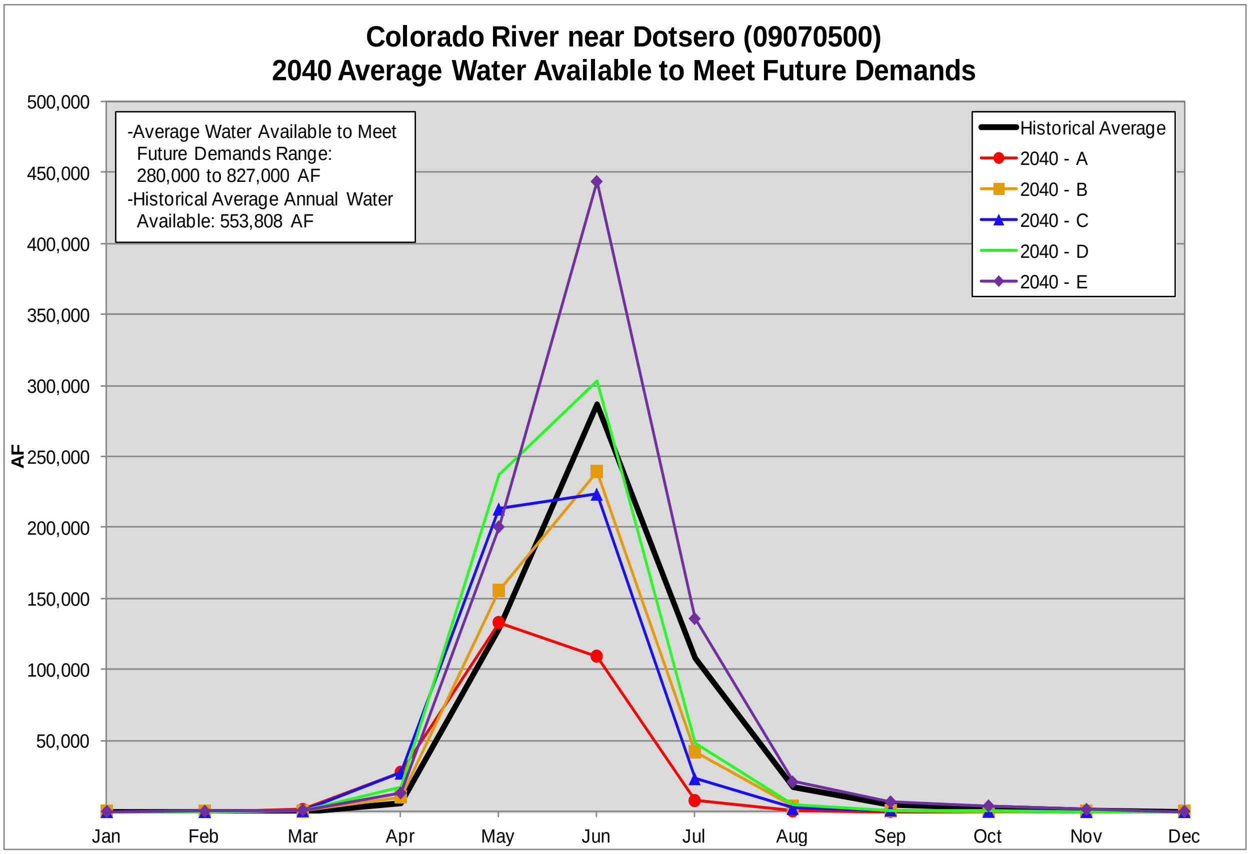


Figure 3-29 – Colorado River near Dotsero - 2040 Average Monthly Water Available to Meet Future Demands

As shown, water available at the upstream Colorado River near Grand Lake gage is much less than the amount of water available at the Colorado River near Dotsero gage. Water available to meet future demand at both locations is reduced because it includes flow allocated to uses downstream of the Colorado River near Dotsero gage, including Grand Valley irrigation demands and Shoshone power demands. Although, there are several tributaries in between the two gages that contribute flow to help meet downstream demands, there are also significant current demands in between the two gages that must be met by a portion of the modeled streamflow at the Colorado River near Grand Lake gage, further reducing available flow. The differences and dependencies between modeled streamflow and water available to meet future demands are highlighted in Table 3-15, that compares average annual modeled streamflow based on historical climate conditions with water available to meet future demands at the two locations.

Table 3-15 – Average Modeled Streamflow and Available Flow at Colorado Gages - Historical Climate

	Colorado River near Grand Lake	Colorado River near Dotsero
Modeled Streamflow (AF/Year)	55,174	1,391,419
Water Available to Meet Future Demands (AF/Year)	10,485	553,808
Difference (Flow Allocated to Downstream Current Demands, AF/Year)	44,689	837,611
% Modeled Streamflow Allocated to Current Demands	81%	60%
% Modeled Streamflow Available to Meet Future Demands	19%	40%

The above table illustrates the following:

- On average, 19 percent of the annual modeled streamflow at the Colorado River near Grand Lake gage is available to meet future demands. On average, 40 percent of the annual modeled streamflow at the Colorado River near Dotsero gage is available to meet future demands.

- Upstream locations on main rivers and smaller tributaries generally have less flow available to meet future demands as a percent of modeled streamflow than gages farther downstream that include more tributary inflow. This is consistent throughout the Study Area.

Figure 3-30 graphically shows the average monthly modeled streamflow compared to water available to meet future demands for historical climate conditions over the 1950 through 2005 study period at the Colorado River near Dotsero gage.

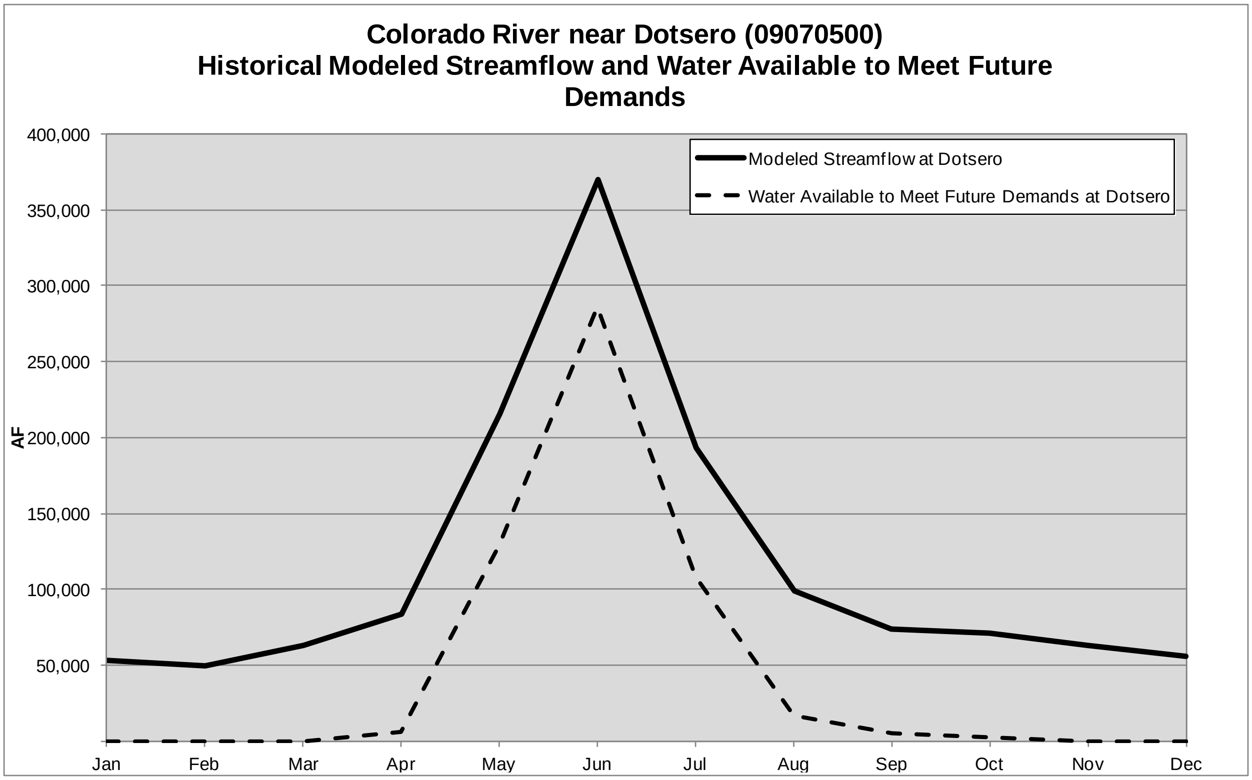


Figure 3-30 – Colorado River near Dotsero - Average Monthly Modeled Streamflow and Water Available to Meet Future Demands for Historical Climate Conditions

Figure 3-30 shows the following:

- During the winter months, there is no flow available to meet future demands at Dotsero. During those months, modeled streamflow is allocated to downstream power demands, including the senior Shoshone Power Plant demand for around 75,000 acre-feet per month.

- In the months with greater physical flow (May, June, and July); more of the modeled streamflow is available to meet future demands. In these months, the non-consumptive Shoshone Power Plant demand is generally satisfied by water flowing through Glenwood Canyon to meet downstream senior irrigation use.

Figure 3-31 shows water available to meet future demands at the Colorado River near Dotsero gage and the downstream Colorado River at Glenwood Springs gage. The primary water use in between these two gages is the Shoshone Power Plant demand. These graphs are presented to better understand modeled streamflow compared to water available to meet future demands.

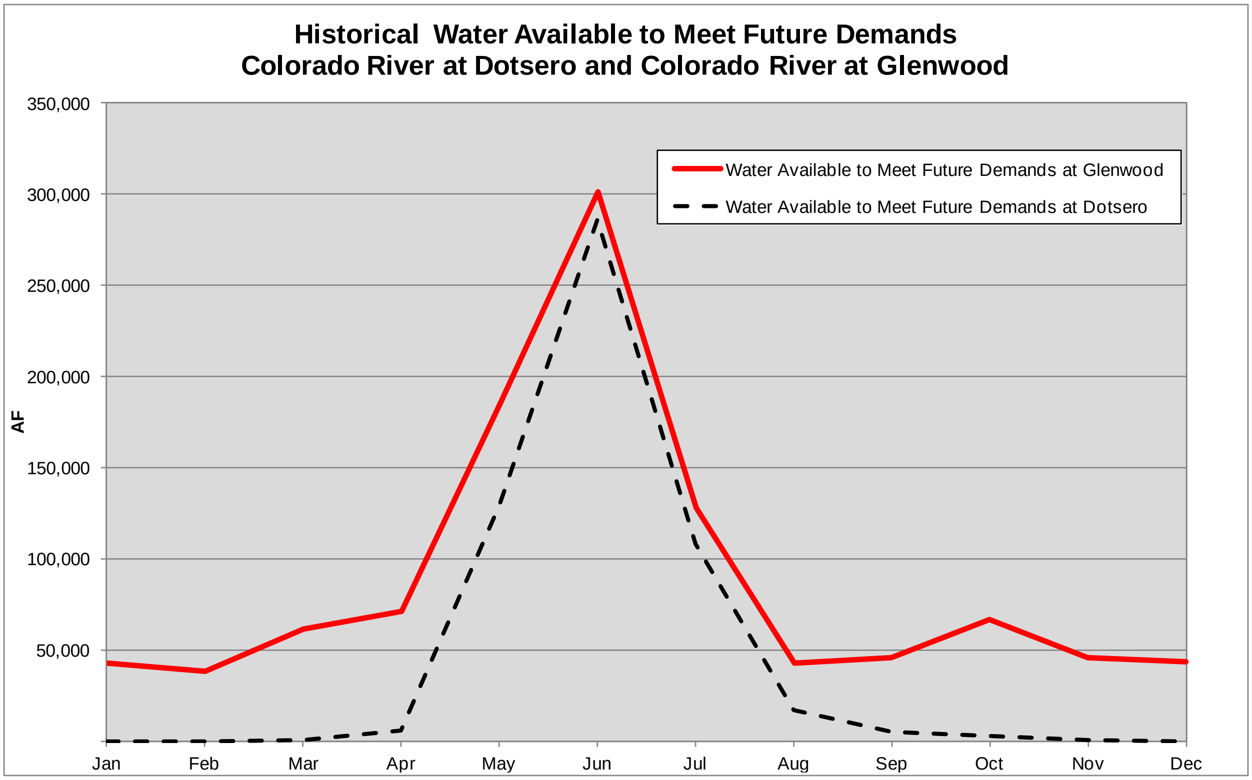


Figure 3-31 – Water Available to Meet Future Demands at Colorado River at Dotsero and Colorado River at Glenwood Springs for Historical Climate Conditions

The following summary is based on Figure 3-31:

- The Colorado River at Glenwood Springs gage is downstream of the Shoshone Power Plant. Figure 3-31, clearly demonstrates that during the non-irrigation season, water becomes available to meet future demands once the senior power right has been satisfied.

2040 Water Available to Meet Future Demands

Figures showing seasonal differences between historical modeled water available to meet future demands and climate projected water available to meet future demands for selected locations in the Study Area are included in Appendix F for the 2040 projections. The 2040 figures are similar to the Figures 3-28 and 3-29 and show the following:

- The climate projections generally indicate more available flow in April and May throughout the Study Area, corresponding to the shift in the natural flow hydrographs discussed in Section 3.4.3.

- The locations in the southern portion of the Study Area show more variation in water available to meet future demands than other locations in the Study Area. This may be in part because, as noted previously, larger scale systems such as the monsoon-based conditions prevalent in the southern areas of the State are not well simulated by climate models.

Appendix F also includes tables summarizing the monthly and annual differences for the 2040 projections. Information in the tables includes average monthly and average annual water available to meet future demands for each of the five projections, and the annual volume reduction and percent reduction from historical. The 2040 tables (Tables F1 through F5) summarizing monthly and annual differences show the following:

- Most locations in the Study Area show less average annual water available to meet future demands compared to historical climate conditions for three of the five projections (2040-A, 2040-B, and 2040-C).
- Locations included in Appendix F throughout the Study Area show more average annual water available to meet future demands compared to historical climate conditions for the 2040-E climate projection.
- Locations in the upper Gunnison basin show an increase in water available to meet future demands for each of the five climate projections in May and June (Taylor River at Almont, East River at Almont, Gunnison River near Gunnison, and Tomichi River Creek at Gunnison). However, available flow for other months is zero at those locations due to the demand for power generation at the Aspinall Unit reservoirs.

Figure 3-32 shows low-flow information at the Yampa River near Maybell gage location. General descriptions for the components of the low-flow comparison charts are provided in Section 3.1.

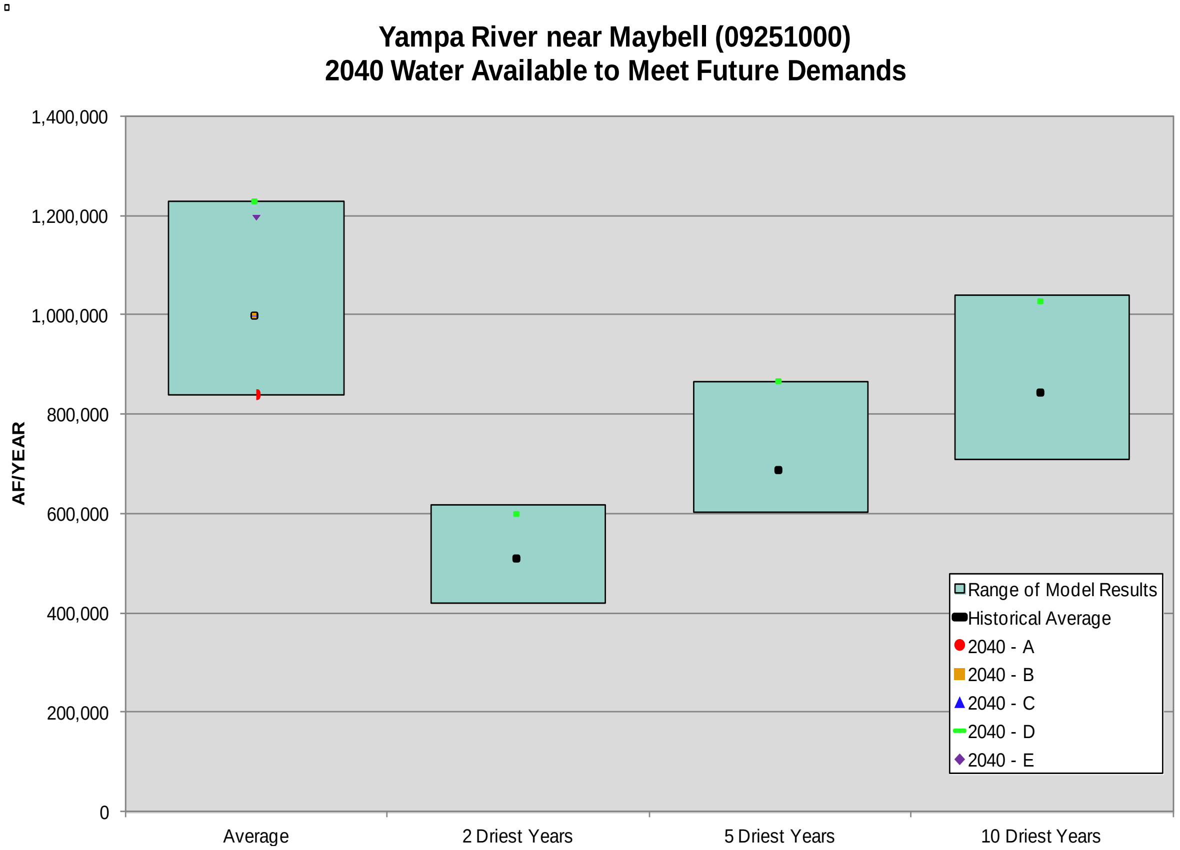


Figure 3-32 – Yampa River near Maybell - 2040 Modeled Streamflow Low-flow Comparison

Low-flow comparison graphs for the selected locations are included in Appendix F for the 2040 climate projections. Similar to the comparison shown in Figure 3-32, the following general observations can be drawn from the 2040 low-flow comparison graphs:

- The historical annual low-flow values fall generally within the 2040 low-flow statistic ranges throughout the Study Area.

2070 Water Available to Meet Future Demands

Figure 3-33 shows the seasonal variation in water available to meet future demands at the Colorado River near Dotsero gage over the 1950 through 2005 study period for the historical model, and for the models representing demands and natural flows adjusted for the 2070 climate projections. Four of the five climate projections show a shift in peak water available from June to May, as compared to a shift in just one climate projections for 2040, as shown in Figure 3-29 above. All of the projections show decreased water available to meet future demands at the Colorado River near Dotsero gage in the summer and fall months.

This trend of increased water available to meet future demands in spring and less during the summer and fall months is generally seen at locations throughout the Study Area, as shown in the figures presented in Appendix F for the 2070 climate projections.

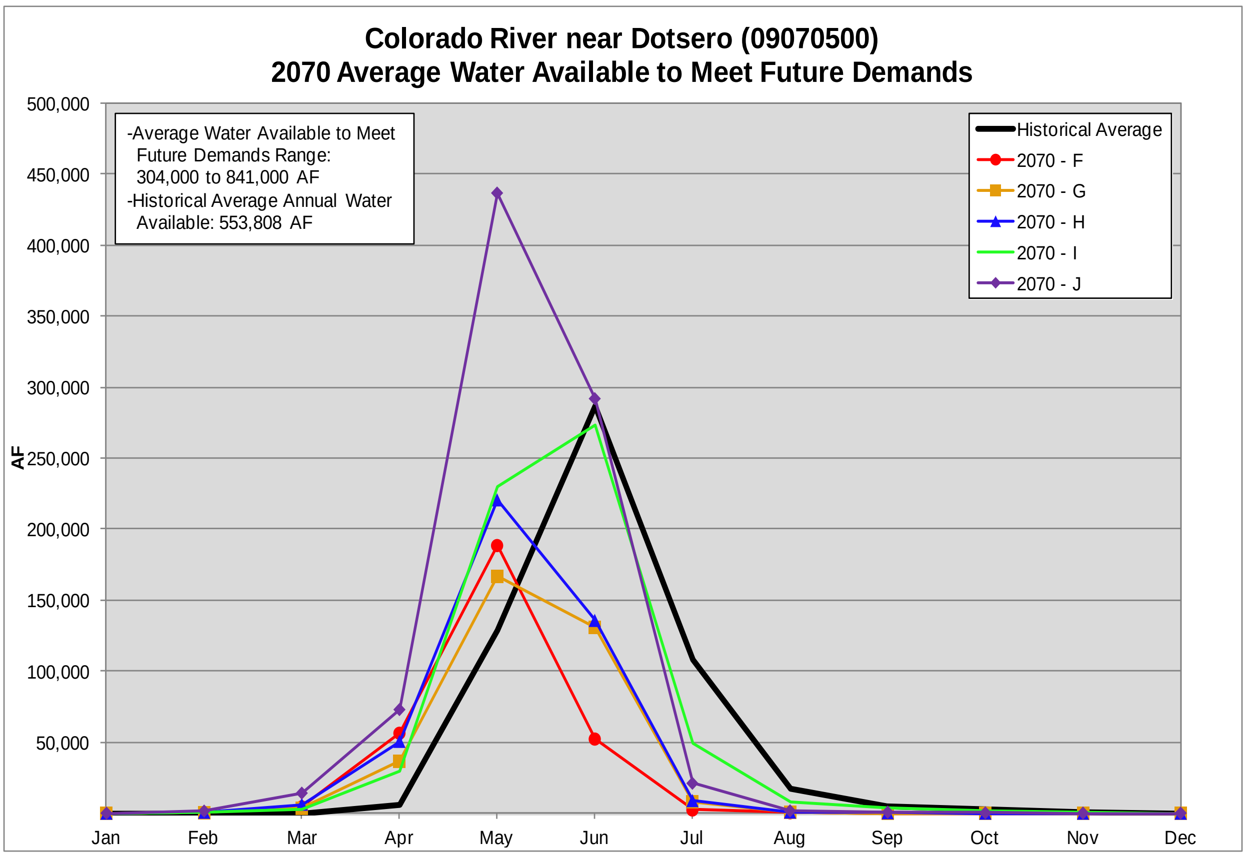


Figure 3-33 – Colorado River near Dotsero - 2070 Average Monthly Water Available to Meet Future Demands

Appendix F also includes tables summarizing the monthly and annual differences for the 2070 projections. Information in the tables includes average monthly and average annual water available to meet future demands for each of the five projections, and the annual volume reduction and percent reduction from historical. The 2070 tables (Tables F6 through F10) summarizing monthly and annual differences show the following:

- Most locations in the Study Area show an increase in average annual water available to meet future demands for climate projection 2070-J compared to historical climate conditions. Notable exceptions in the southwestern portion of the Study Area include Uncompahgre River at Delta, Dolores River near Bedrock, and San Miguel River at Naturita.

- Similar to 2040, locations in the upper Gunnison basin show an increase in water available to meet future demands for each of the five climate projections in May and June (Taylor River at Almont, East River at Almont, Gunnison River near Gunnison, and Tomichi River Creek at Gunnison). In contrast to 2040, there is available flow in April, on average, for three of the climate projections. Available flow for other months is zero at those locations, again reflecting power generation demands at the Aspinall Unit reservoirs.

Low-flow comparison graphs for the selected locations are included in Appendix F for the 2070 climate projections. The following general observations can be drawn from the 2070 low-flow comparison graphs:

- The historical annual modeled streamflow generally falls within the low-flow statistic ranges for the 2070 climate projections in the Yampa, White and Colorado basins. However, the low-flow ranges for the climate projections are lower than historical annual low-flow values for most locations in the lower Gunnison basin and the southwestern portion of the Study Area.

- Annual low-flow statistic values in the northern portion of the Study Area show a wider range between the five individual 2070 climate projections than between the five individual 2040 climate projections. However, annual low-flow statistic values in the central and southern portion of the Study Area show a narrower range between the five individual 2070 climate projections than between the five individual 2040 climate projections.

Where to find more detailed information:

Water available to meet future demands based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for locations represented in the CRWAS modeling effort through the CRWAS Data Viewer (http://cwcb.state.co.us/).

3.6.3 *Modeled Reservoir Storage*

The StateMod models include over 60 operating reservoirs in the Colorado River basin in Colorado. Several of the larger reservoirs are operated for direct transbasin diversions or for exchange to allow transbasin diversions (Granby, Shadow Mountain, Williams Fork, Dillon, and Green Mountain). Storage and releases from these reservoirs do not primarily satisfy demands in the Study basins and, as noted in Section 2.3.6, potential increased demand in the South Platte River and Arkansas River basins due to climate change have not been addressed in the

Phase I CRWAS modeling efforts. Transbasin demands are expected to be revisited during Phase II of the CRWAS project. In addition, the Aspinall Unit reservoirs (Blue Mesa, Morrow Point, and Crystal) are primarily operated by the USBR for hydropower use not directly affected by increased irrigation demand due to climate projections.

To understand the effects of climate projections on storage, six reservoirs were selected for inclusion in the report that are used primarily or partially to supplement irrigation demands. Generally from the north to south in the Study Area, the reservoirs selected include Yamcolo, Green Mountain, Vega, Blue Mesa, Ridgway, and McPhee. These reservoirs are impacted by changes in timing and volume of natural flow, and by changes to CIR due to projected temperature changes. Operations of the reservoirs were not revised for the modeling efforts; only current operational strategies are represented.

Reservoir storage, releases, and associated end-of-month content based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for each of the 60-plus reservoirs represented in the CRWAS modeling effort through the CRWAS Data Viewer.

2040 Modeled Reservoir Storage

Figure 3-34 shows the time series of modeled reservoir end-of-month contents based on historical climate and the 2040 climate projections for Yamcolo Reservoir, located in the upper reaches of the Yampa River basin. Yamcolo Reservoir is primarily used to meet late season irrigation demands, and also has an account for municipal and industrial use. Although the model study period is 1950 through 2005, the graph only shows 1980 through 2005 to enhance readability.

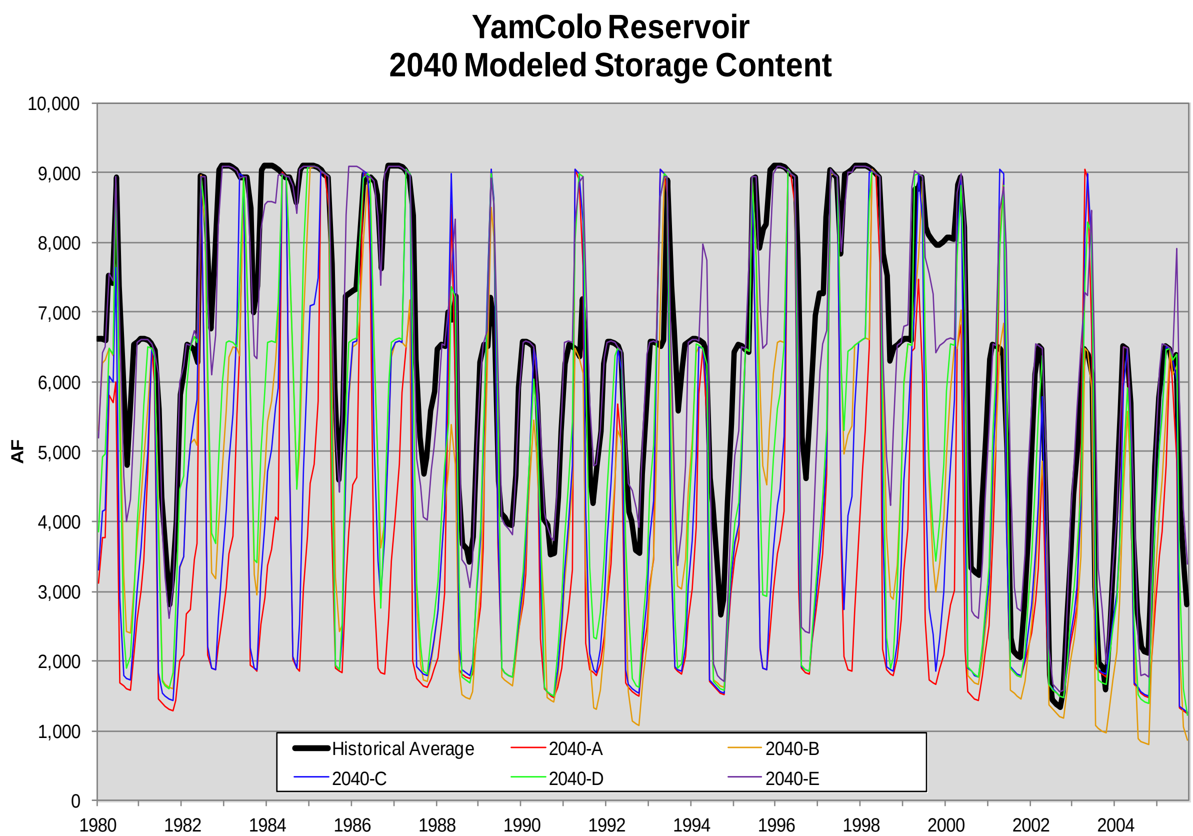


Figure 3-34 – Yamcolo Reservoir - 2040 Modeled Storage Content

As discussed in previous sections, the Yampa River basin generally shows increases in average annual modeled streamflow for the five climate projections. However, the increased flow is associated with an earlier peak runoff, and flows are below historical during the late irrigation season. Decreased late irrigation season flows, coupled with increased irrigation demands due to increased temperatures, result in more reservoir releases required to meet the demands. Figure 3-34 shows that Yamcolo Reservoir draws down more than historical levels during the 1980s and the late 1990s. Increased spring flows result in the reservoir filling more than historical for some of the model projections.

Figure 3-35 shows average monthly modeled Yamcolo Reservoir content over the 1950 through 2005 study period for historical climate conditions, and average monthly content for each of the 2040 climate projections. As shown, the reservoir is drawn down more with the climate projection hydrology and demands than under historical climate conditions. Note that Yamcolo Reservoir has a conservation pool, plus a municipal and industrial account that is not modeled with increased demand under climate projections.

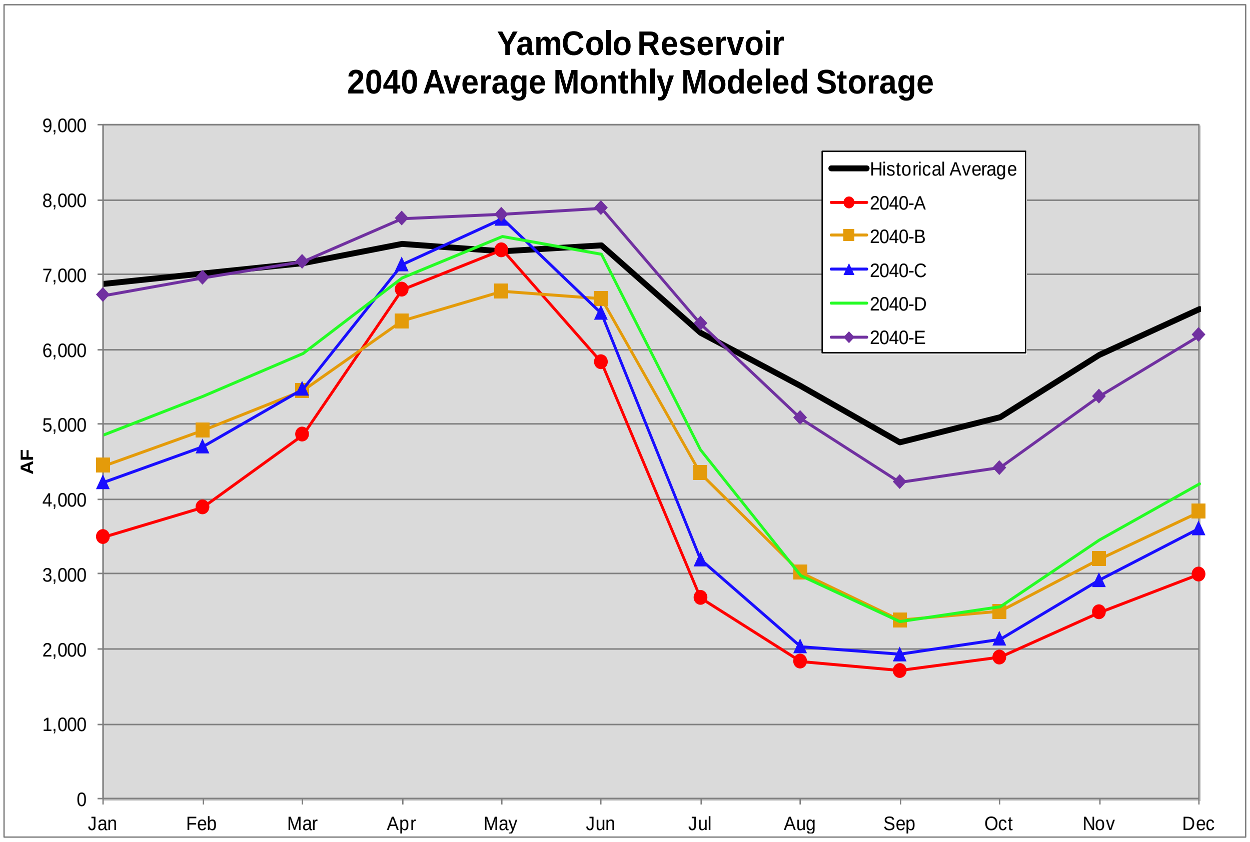


Figure 3-35 – Yamcolo Reservoir - 2040 Average Monthly Modeled Storage Content

Figures showing end-of-month content time-series and seasonal differences between historical modeled reservoir content and climate projected reservoir content for the selected reservoirs are included in Appendix G for the 2040 projections. The Appendix figures are generally similar to the Figure 3-34 and show the following:

- Earlier peak runoff, reduced flows during the peak irrigation season, and increased crop demands associated with each of the five climate projections result in more use of reservoir storage (more reservoir fluctuation) compared to use of storage under historical climate conditions.

- There are a few years when the reservoirs presented in Appendix G show maximum annual storage greater than historical maximum annual storage for the 2040-E climate projection. This corresponds to higher natural flows and lower temperature increases for that projection in the same years.

- In most years, reservoirs are drawn down to a lower level for the five climate projections. However, Yamcolo Reservoir, Green Mountain Reservoir, and Ridgway Reservoir fill to the same maximum storage as simulated under historical climate conditions in most years. McPhee Reservoir and Vega Reservoir generally fill to the same level as historical climate conditions for only one projection (2040-E); whereas Blue Mesa generally did not fill to the historical climate condition levels for any of the climate projections.

2070 Modeled Reservoir Storage

Figure 3-36 shows the time series of modeled reservoir end-of-month contents based on historical climate and the 2070 climate projections for Yamcolo Reservoir. Although the model study period is 1950 through 2005, the graph only shows 1980 through 2005 to enhance readability.

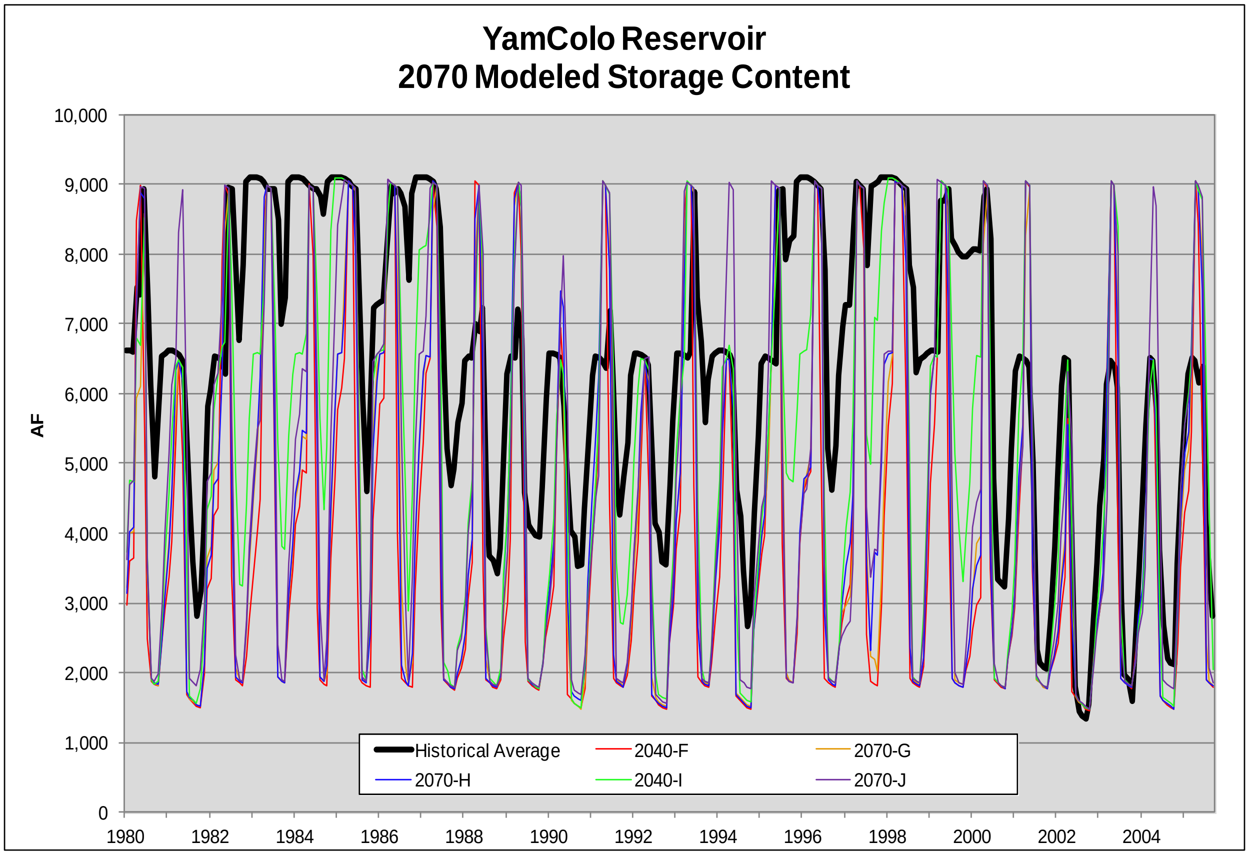


Figure 3-36 – Yamcolo Reservoir - 2070 Average Monthly Modeled Storage Content

Figures showing end-of-month content time-series and seasonal differences between historical modeled reservoir content and climate projected reservoir content for the selected reservoirs are included in Appendix G for the 2070 projections. The Appendix figures are generally similar to the Figure 3-36 and show the following:

- Earlier peak runoff, reduced flows during the peak irrigation season, and increased crop demands associated with each of the climate projections result in more use of reservoir storage compared to use of storage under historical climate conditions.
- In general, the reservoirs show higher fluctuations in storage for the 2070 climate projections compared to the 2040 climate projections.
- On average, YamColo Reservoir is able to fill to maximum content for each of the five climate projections, more than historical climate conditions and 2040 climate projections, even though the reservoir drawdown is significantly greater than under historical conditions. Ridgway Reservoir and Green Mountain Reservoir are able to fill

to historical for some of the climate projections. Blue Mesa Reservoir, Vega Reservoir, and McPhee Reservoir do not fill to historical levels for any of the climate projections.

Where to find more detailed information:

Reservoir storage, releases, and associated end-of-month content based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for each of the 60-plus reservoirs represented in the CRWAS modeling effort through the CRWAS Data Viewer (http://cdss.state.co.us/).

3.6.4 *Modeled Consumptive Use*

Crop irrigation demands for the climate projections increased in each study basin, due to increases in temperature and decreases in irrigation season precipitation. As discussed in Section 2.3.6, StateMod head gate demands for irrigation structures were adjusted for each climate projection. Transbasin diversion demands, demands for municipal and industrial use, and instream flow demands were not revised. Transbasin and municipal demands under climate projected conditions are expected to be revisited during Phase II of the CRWAS project.

2040 Modeled Consumptive Use

Figure 3-37 shows the average monthly modeled consumptive uses and losses in the Yampa River basin for each of the five 2040 climate projections and for historical climate conditions. Values are the total modeled depletions in the basin and include irrigation, municipal, and industrial consumptive uses plus reservoir evaporation.

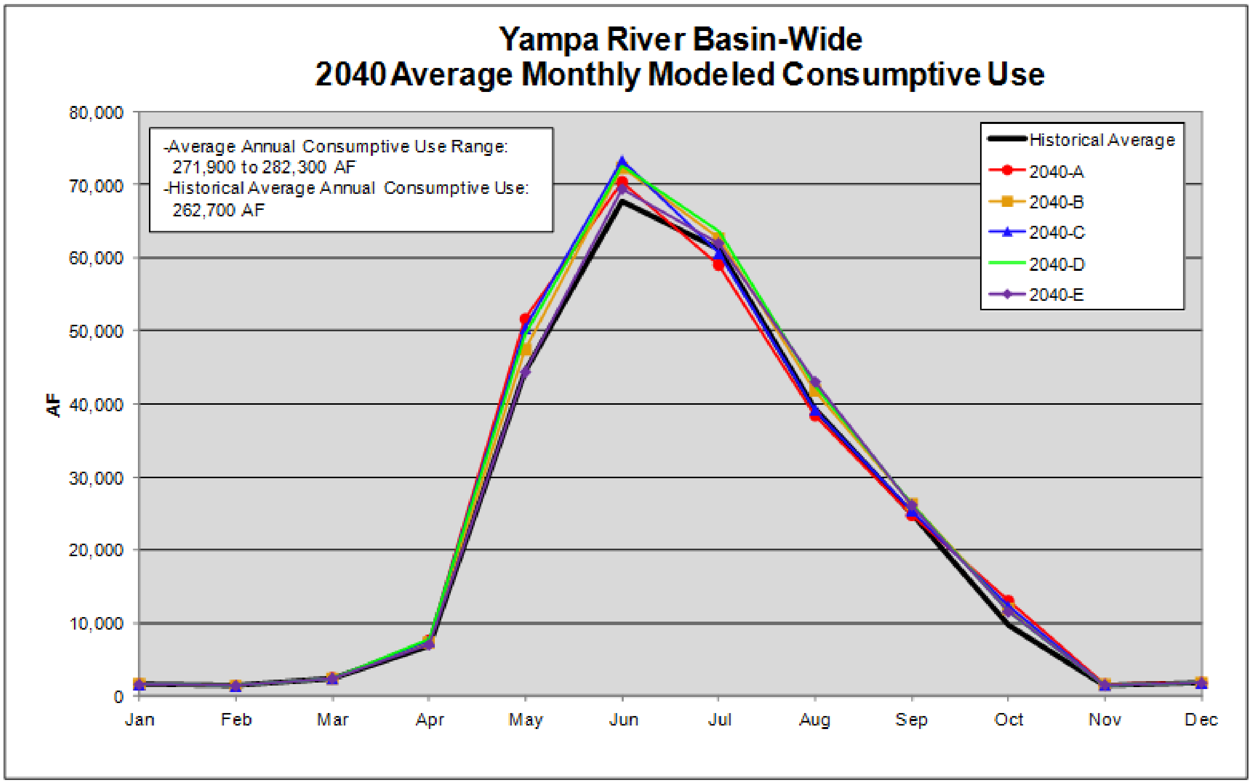


Figure 3-37 – Yampa River Basin-Wide - 2040 Average Monthly Modeled Consumptive Use

As shown, average monthly consumptive use in the Yampa River basin increases over historical climate conditions every month during the irrigation season for most of the 2040 climate projections. The only exception occurs with climate scenario 2040-A when average monthly consumptive use decreases during the month of July.

Table 3-16 shows the 2040 average annual basin consumptive use compared to historical basin consumptive use for each climate projection. To provide a comparison with the Consumptive Uses and Losses Report, developed by the U.S. Bureau of Reclamation to meet Upper Colorado River Compact reporting requirements, reservoir evaporation from the Aspinall Unit reservoirs (Blue Mesa, Morrow Point, and Crystal) are not included in the values for the Gunnison basin provided in Table 3-16. Aspinall Unit reservoir evaporation, however, is modeled by the CRWAS and decreases from historical conditions by between 600 and 3,000 acre-feet per year for the 2040 climate projections.

Table 3-16 – 2040 Average Annual Study Basin Increase in Consumptive Use Compared to Historical Conditions (AF)

Study Basin	Historical Basin CU (AF)	Increase In CU (AF) for Climate Projections						
		2040-A	2040-B	2040-C	2040-D	2040-E	Comb. Ave	Comb. % Increase
Yampa	262,723	10,674	15,504	14,481	19,527	9,174	13,872	5%
White	50,096	12,039	8,515	11,198	9,144	4,203	9,020	18%
Upper Colorado	1,195,107	14,446	46,843	58,474	67,060	48,492	47,063	4%
Gunnison*	592,758	48,588	60,669	70,827	69,661	40,707	58,090	10%
San Juan/Dolores	606,069	-100,956	-17,606	-7,091	15,753	46,143	-12,751	-2%
Total	**2,706,753**	**-15,209**	**113,925**	**147,889**	**181,145**	**148,719**	**115,294**	**4%**

Consumptive use average monthly comparison graphs for the 2040 climate projections and historical conditions for each Study basin, similar to Figure 3-37, are included in Appendix H. The Appendix H figures and Table 3-16 generally show the following:

- Average annual consumptive use in the Yampa, White, Upper Colorado, and Gunnison basins are greater than historical conditions for every 2040 climate projection. The average annual consumptive use in the San Juan is less than historical conditions for three of the five climate projections (2040-A, 2040-B, and 2040-C).

- Consumptive use is higher for most months in every basin except the San Juan. The San Juan shows higher consumptive use in spring months for every climate projection except 2040-A.

- Total consumptive use for the Study Area is greater than historical climate conditions for every climate projection except 2040-A.

- Although consumptive use generally increases, not all crop demands are met in any basin. Similar to historical climate results, there continue to be water shortages on tributaries and in the late irrigation season for the climate projections. Note that historical and climate projection crop shortages are difficult to compare directly, since the crop demands are not the same.

2070 Modeled Consumptive Use

Figure 3-38 shows the average monthly modeled consumptive uses and losses in the Yampa River basin for each of the five 2070 climate projections and for historical climate conditions. Values are the total modeled depletions in the basin and include irrigation, municipal, and industrial consumptive uses plus reservoir evaporation.

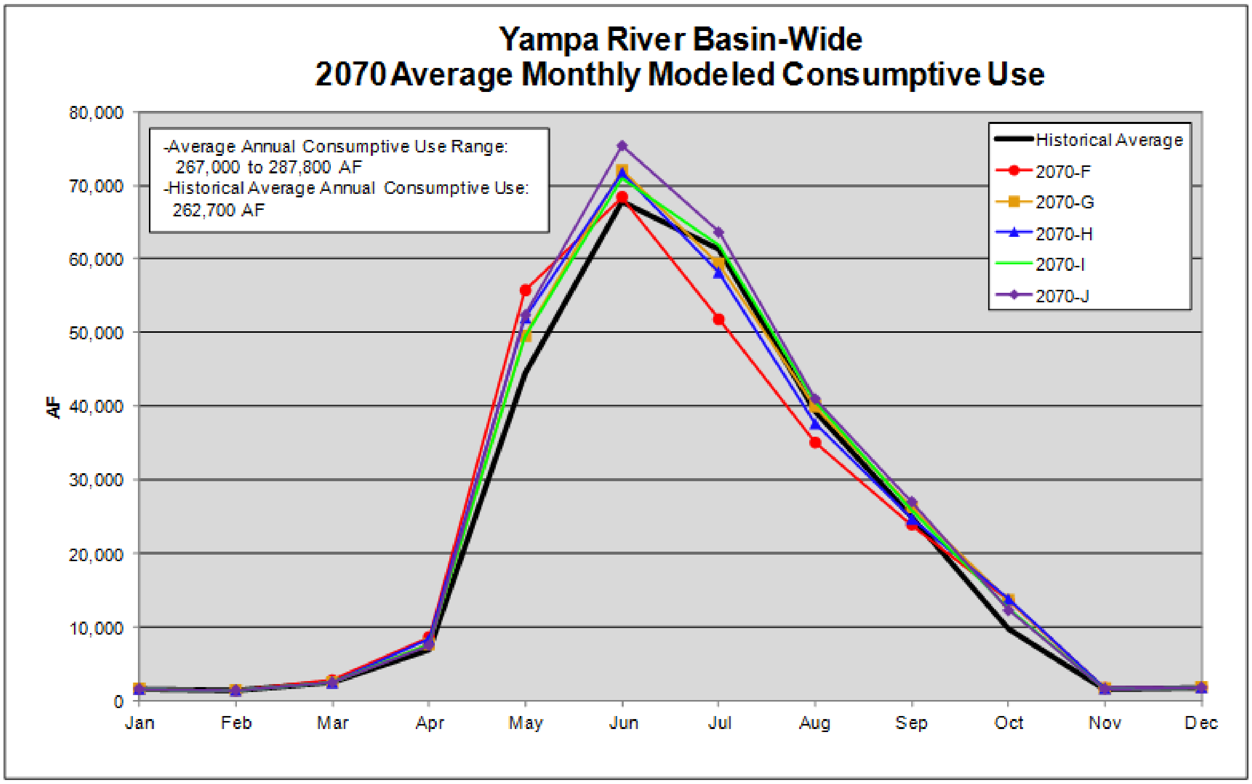


Figure 3-38 – Yampa River Basin-Wide - 2070 Average Monthly Modeled Consumptive Use

As shown, average monthly consumptive use in the Yampa River basin increases over historical climate conditions in April, May, and June for each of the 2070 climate projections, and decreases for three of the projections in July through September.

Table 3-17 shows the 2070 average annual basin consumptive use compared to historical basin consumptive use for each climate projection, and compared to historical. To provide a comparison with the Consumptive Uses and Losses Report, developed by the U.S. Bureau of Reclamation to meet Upper Colorado River Compact reporting requirements, reservoir evaporation from the Aspinall Unit reservoirs (Blue Mesa, Morrow Point, and Crystal) are not included in the values for the Gunnison basin. Aspinall Unit reservoir evaporation, however, is modeled in the CRWAS, and decreases from historical conditions by between 3,000 acre- and 8,000 acre-feet per year for the 2070 climate projections.

Table 3-17 – 2070 Average Annual Study Basin Increase in Consumptive Use Compared to Historical Conditions (AF)

Study Basin	Historical Basin CU (AF)	Increase In CU (AF) for Climate Projections						
		2070-F	2070-G	2070-H	2070-I	2070-J	Comb. Ave	Comb. % Increase
Yampa	262,723	3,353	14,453	12,384	14,899	25,035	14,025	5%
White	50,096	15,111	12,825	12,817	9,195	14,660	12,922	26%
Upper Colorado	1,195,107	22,584	35,804	47,368	64,819	103,838	54,883	5%
Gunnison	592,758	58,027	66,411	78,499	68,000	114,982	77,184	13%
San Juan/Dolores	606,069	-114,893	-94,794	-45,660	-18,915	5,623	-53,728	-9%
Total	**2,706,753**	**-15,818**	**34,699**	**105,408**	**137,998**	**264,138**	**105,285**	**4%**

Consumptive use average monthly comparison graphs for the 2070 climate projections and historical conditions, similar to Figure 3-38 for each Study basin, are included in Appendix H. The Appendix figures and Table 3-17 generally show the following:

- Average annual consumptive use in the Yampa, White, Upper Colorado, and Gunnison basins are greater than historical conditions for every 2070 climate projection. The average annual consumptive use in the San Juan is less than historical conditions for each of the 2070 climate projections except 2070-J.

- Consumptive use is generally higher in April, May, and June for every basin for each of the 2070 climate projections with the exception of the San Juan basin. Consumptive use is higher in every month in the White River basin.

- Total consumptive use for the Study Area is greater than historical climate conditions for every climate projection except 2070-F.

- The combined average consumptive use is higher for the 2070 projections compared to the 2040 projections in every basin except the San Juan.

- Although consumptive use generally increases, not all crop demands are met in any basin. Similar to historical climate results, there continue to be water shortages on tributaries and in the late irrigation season for the climate projections. Note that historical and climate projection crop shortages are difficult to compare directly, since the crop demands are not the same.

Where to find more detailed information:

Consumptive use for diversions based on historical, alternate historical, and alternate climate projections can be accessed, viewed, and saved for each demand location represented in the CRWAS modeling effort through the CRWAS Data Viewer (http://cdss.state.co.us/).

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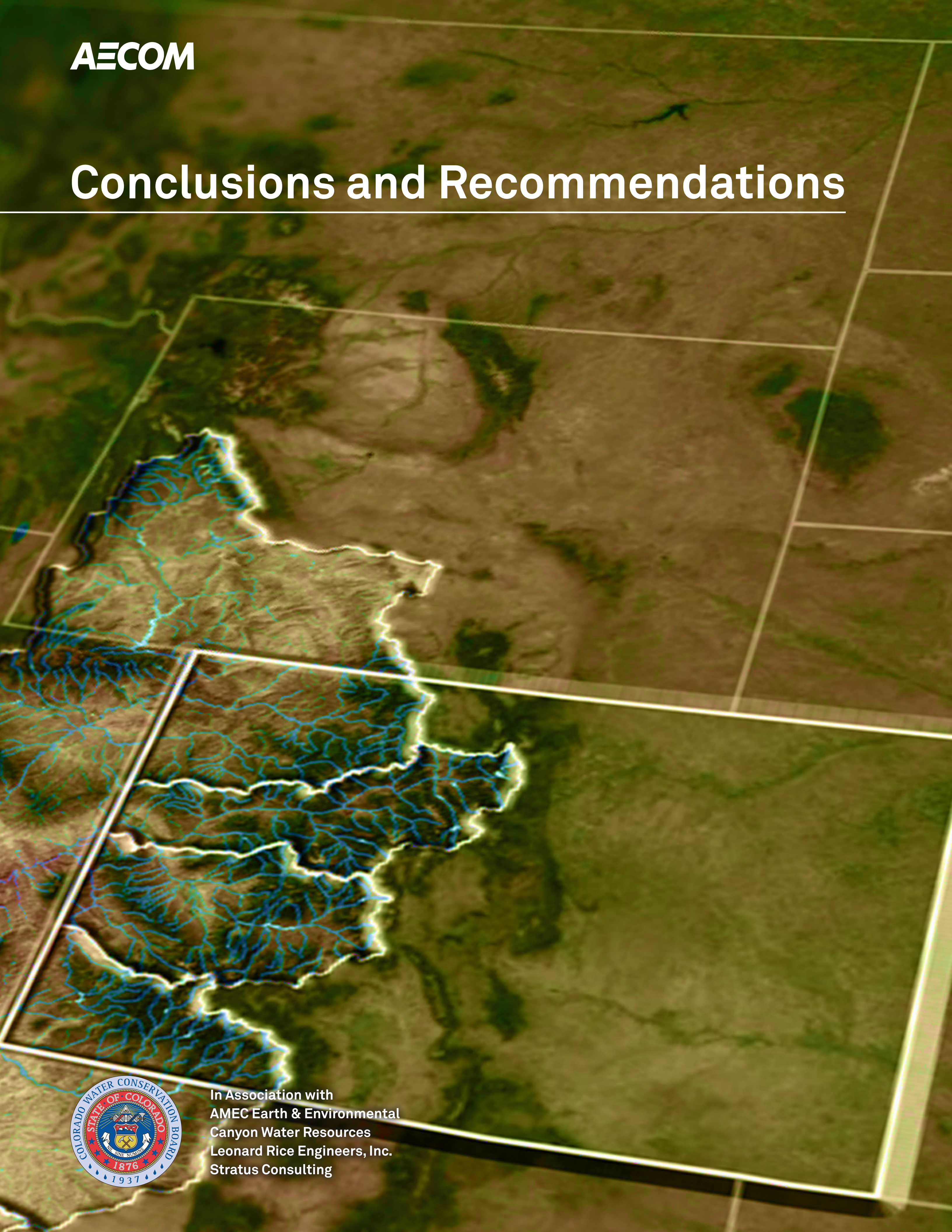
Conclusions and Recommendations



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4 CONCLUSIONS AND RECOMMENDATIONS

Phase I of the CRWAS responds to the General Assembly's direction to the CWCB to provide information on how much additional water is available from the Colorado River basin to meet the State's future consumptive and non-consumptive water needs. In accordance with IBCC input in the scoping process, Phase I presents water availability based on current levels of water use, existing water supply systems, and current interpretations of operating and management practices.

An important aspect of the Phase I work is that it is transparent and accessible. Analysis methods and refinements to modeling tools were reviewed extensively with BRT representatives, including the owners and operators of the major water supply systems. Results are presented for three alternative hydrologic cases, including those based solely on historical hydrology. This process allows individuals and agencies to consider a broad range of potential future hydrologic conditions in their water management decisions.

Because of that transparency, the tools, and the detailed database of natural flows, water use and modeled conditions provided by Phase I will serve as a foundation for future Study phases and other analyses, by the State and others. Subsequent CRWAS phases would likely consider potential new water supply projects, additional non-consumptive water demands and revised water management strategies intended to meet those demands to the greatest degree with consideration for acceptable risk.

Important conclusions and recommendations of the Phase I Study are summarized in four general categories: Technical; Study Processes and Supporting Accomplishments; Utilization of Phase I Results, and Future Analyses.

4.1 Technical Results

The technical approach and findings presented in the previous sections document the geographic breadth and engineering sophistication of the CRWAS. The datasets and modeling tools of the State's CDSS proved to be well-suited for addressing current water management operations and the effects of potential future hydrologic conditions. Extensive streamflow, reservoir storage, consumptive use and other important data are now available throughout the Study Area for current water management operations superimposed on historical hydrology, extended historical hydrology and climate-adjusted hydrology.

1. **Historical Hydrology -** The analysis of Historical Hydrology results in new water resource data throughout the Study Area based on the latest adjustments to the CDSS models. Historical hydrology has long been used in estimating the reliable yields of Colorado water supply systems. The magnitude and duration of droughts in relation to the wet periods that refill reservoirs are critical in analyzing our ability to meet current and future consumptive and non-consumptive water needs. The longest wet spells in the 56-year record (referred to as the "historic spell") range from 4 to 16 years in length across the 227 locations in the Study Area where natural flows are determined, with only 4 percent of historic wet spells longer than 7 years. Historic dry spells range from 3 to 11 years in length with 95 percent of dry spells being 5 or 6 years long. Moving from north to south, historic dry spells generally become shorter and historic wet spells generally become longer.

2. **Extended Historical Hydrology -** The Extended Historical Hydrology showed that the length, intensity and frequency of wet and dry spells vary significantly across the Study Area. The expected frequency with which a dry or wet spell of length equal to the historic spell will return also varies considerably from location to location, so conclusions about the expected recurrence of spells must be made on a site-specific basis. In general, the Extended Historical Hydrology shows that significantly longer dry periods occurred prior to recorded history.

3. **Climate-Adjusted Hydrology -** For the Climate-Adjusted Hydrology, some projections of future conditions show increased flows at the majority of locations, compared to historical conditions; however, most projections show reduced flows. Projected flows generally show a shift toward earlier runoff. At most locations and for most projections, future conditions show an increase in precipitation in the winter and a decrease in precipitation during the summer. All projections show an increase in temperature. Decreased precipitation and increased temperature during the growing season lead to increased crop irrigation requirement. This, combined with a tendency for runoff to occur earlier, contributes to increased fluctuation in reservoir contents and, generally, lower end-of-year contents. The projections also indicate that the southern part of the State may be generally drier (less Natural Streamflow, Modeled Streamflow, and Water Available to Meet Future Demands) than northern parts of the State.

Readers are encouraged also to review the details presented in Table ES-2, the main report and its appendices as well as the on-line CRWAS Data Viewer to gain a more complete understanding of water availability in the Study Area.

4.2 Study Processes and Supporting Accomplishments

1. **IBCC and BRT Involvement** – Interaction with the IBCC and the BRTs provided essential context for the work performed, especially concerns regarding the Study's methods and outcomes. The interaction helped mold the Study and ensure that the results of the initial CRWAS process provide a strong foundation for future work. The interaction and educational workshops also facilitated improvements and enhanced trust in the State's CDSS planning tools.

2. **Public Outreach** –General public input also shaped the Phase I study. Numerous meetings, including but extending well beyond the official IBCC and BRT meetings, provided important forums for sharing the complex issues and tools of the CRWAS. Formal comments provided by more than 30 entities on the Draft CRWAS Phase I Report helped improve the Study and its results. These comments were carefully considered by the CRWAS Team and, in response, the CWCB authorized extensive additional outreach workshops and the preparation of a 115-page response matrix. The response matrix provides the State and its water stakeholders with valuable documentation about water management concerns and supports statewide communication and collaboration in water planning. As the Study transitions into additional phases, a similar level of outreach may be an important part of intrastate dialogue to guide water supply and demand analyses for a variety of potential planning scenarios. Public outreach should continue to include education and review of CDSS models; ongoing refinements are recommended to advance the value of the State's analysis tools.

3. **Access to Data and Modeling Results** – Water availability is highly dependent on the characteristics of a particular use—the priority and magnitude of its water rights, the physical supply available at its location and the capacity of its facilities. No single report can provide enough detail to address the thousands of Colorado water uses within the Colorado River Basin. Through the CRWAS public outreach activities, it became clear that stakeholders required simplified access to all of the detail of the CRWAS data and modeling results in order to use the Study results effectively. An online CRWAS Data Viewer now provides a means to quickly and easily:

   - Explore over 2,000 CRWAS model locations on interactive maps.
   - View and compare streamflows, reservoir contents, diversions and other data for the 5,500 final CRWAS model runs representing historical, alternate historical, and climate projected conditions.
   - Download CRWAS model data in user-friendly spreadsheet format for stakeholders to prepare additional analyses and tailor their own presentations.

   The CRWAS Data Viewer allows anyone with internet connection to easily access hundreds of gigabytes of CRWAS information without having to download and learn new and complex software. This application will help stakeholders consider their own assessments of future opportunities and risks. The CRWAS Data Viewer and corresponding User Manual are available through an internet link on the CWCB website. During CRWAS public outreach workshops, CWCB received positive feedback on the usefulness of the CRWAS Data Viewer. This application should be updated, as necessary, to respond to initial public use and to allow continued public use through subsequent phases of the CRWAS and other state programs.

4.3 Utilization of Phase I Results

1. **Support for other State Programs** – As listed on Figure ES-2, the many ongoing State-sponsored programs and processes are interconnected with each other and with the CRWAS. Hydrologic data and modeling tools from CRWAS Phase I and subsequent phases will support many other State programs and processes. CRWAS can also support several of Governor Hickenlooper's goals for the IBCC and BRTs in further implementation of the Water for the 21st Century Road Map including:

   - Increase education, specificity, support, engagement, and regional cooperation in the IBCC framework.
   - Support common understanding of statewide water problems and solutions.
   - Support interchange of ideas between State, water providers, and project proponents.
   - Support BRT portfolio development and assist in identifying methods to meet regional needs.

2. **Availability of Results for Historical Hydrology** – Traditionally, water supply agencies have relied extensively on historical information on water supply as an indication of likely future conditions, the premise being that history tends to repeat itself. Because the CRWAS also includes analyses for paleohydrology and climate change hydrology, much of the focus in public outreach meetings and in presenting Phase I results necessarily focused on aspects of these less-familiar topics. The data and modeling results for today's level of demands superimposed on historical natural flows

are presented in Phase I of the CRWAS and available through the CRWAS Data Viewer. This information provides the foundation on which stakeholders' can assess their future water management strategies.

3. **Perspectives on Climate Change Projections** – Phase I of the CRWAS compares the effects of three alternative water supply cases (historic hydrology, extended historical hydrology, and climate-adjusted hydrology). Phase I results and models allow Colorado River water managers, policy makers, and stakeholders to consider wide ranging hydrologic scenarios and base their water management decisions on their own risk management strategies. With the CRWAS information, they can base their planning decisions on their own level of confidence in the historic hydrology, paleohydrology, or climate-adjusted hydrology.

4. **Perspectives on Uncertainty** – The CRWAS addressed the uncertainty in projections of future climate conditions by selecting five climate "cases" for each future time frame. The projections were selected to cover approximately 80 percent of the range of conditions projected by the 112 readily available climate model runs. The results of the CRWAS analyses, which are based in part on the selected projections, reflect the uncertainties in climate modeling. The range of results is large—in some cases and locations the selected climate projections lead to higher streamflows and in some cases they lead to lower streamflows; and this is a realistic reflection of the state of climate science at this time.

5. **Foundation for Water Resource Planning –** Phase I is not prescriptive, with no grand conclusions suggesting that water managers take specific actions. Instead, Phase I provides a tremendous amount of data about a variety of possible future hydrologic conditions, allowing study users the freedom to interpret the data in context with their own programs, priorities and water management systems. Based on comments received on the previous draft report, many water agencies may focus on historic hydrology in the planning and financing of major capital investments but may also consider, in a more qualitative fashion, the impact of potential climate change on these decisions. This approach anchors the policy-making process in the context of the historical hydrology while still considering vulnerabilities that may be faced if the future hydrologic conditions prove to be significantly different than they have been in the past.

4.4 Future Analyses

1. **Stakeholder Interest in Assessment of Water Availability under Future Demands** – Phase I results are based only on current water uses (current irrigated acreage, M&I demands, and non-consumptive water demands). In the Study presentations and workshops, and in written comments submitted on the previous draft report, many stakeholders expressed interest in the analysis of water availability considering future levels of consumptive and non-consumptive water demands, and analysis of potential water supply solutions including new water supply projects, new non-consumptive use programs and protections, and new water management strategies - all supporting a more robust assessment of risk management strategies.

2. **Alternative Transbasin Water Demands affected by Climate Change** – Climate change in eastern Colorado may affect demands for Colorado River water. In Phase I of the CRWAS, transbasin demands were not adjusted to reflect the effects that climate change may have on current levels of demand in the South Platte River and Arkansas River basins. As the State continues its programs to develop Decision Support Systems

for the South Platte and Arkansas River basins, the methods adopted in the CRWAS may be appropriate to estimate projected climate-adjusted water availability for these adjacent river basins.

3. **Consider Alternative Water Management Strategies and Interpretations of Existing Operational Agreements** – Phase I results indicated that, under hydrologic conditions not experienced in the historic period, existing operational agreements, management plans, and annual reservoir operation plans may need to be interpreted in the context of these potential changed conditions. Subsequent phases of the CRWAS will provide opportunities to assess the effects of a broad range of reasonable interpretations and consider alternate operational strategies, including formal and informal agreements, affecting water management in the Study Area.

4. **Collaboration with Other Studies and Incorporation of Independent Reviews of Methods and Results** – Phase I demonstrated the benefits of independent input received from the IBCC, the BRTs, and other stakeholders and groups. Colorado is in an enviable position in terms of its resident professional expertise in water resource planning and management, its existing CDSS modeling tools, and the extensive climate change expertise in the state. Future CRWAS phases should continue to build upon the multiple CWCB / IBCC programs. Use of the CCTAG as a cost-effective and independent technical reviewer should continue, which will enhance the credibility of the State's programs like the CRWAS.

Final Thoughts for Colorado River Stakeholders

Phase I of the CRWAS provides Colorado River stakeholders with updated computer models and important new information on historic and future water availability. The CRWAS provides twelve different water supply scenarios based on historical hydrology, paleohydrology, and the ten climate change projections. The broad range of projected conditions poses a daunting challenge to planning. There is no single way to move forward with planning for water supply under profound uncertainty, but researchers and water resources managers are already developing planning approaches that begin to address the new types of uncertainty about long-term conditions. Scientists have been able to provide only very general (and sometimes contradictory) guidance about how to interpret projections of future conditions, but water managers have begun to consider practical ways to address uncertainty, and some useful resources are referenced in the body of this report.

Phase I results can be used by stakeholders to consider a broad range of potential future hydrologic conditions, better understand uncertainty in water management decisions, and support the development of specific policies and programs. It is recommended that each stakeholder entity interpret Phase I work from its own perspective, considering its own assessment of the possible future conditions, its role in water management, the resources it has at hand with which to adapt to alternative potential futures, and its tolerance for risk.

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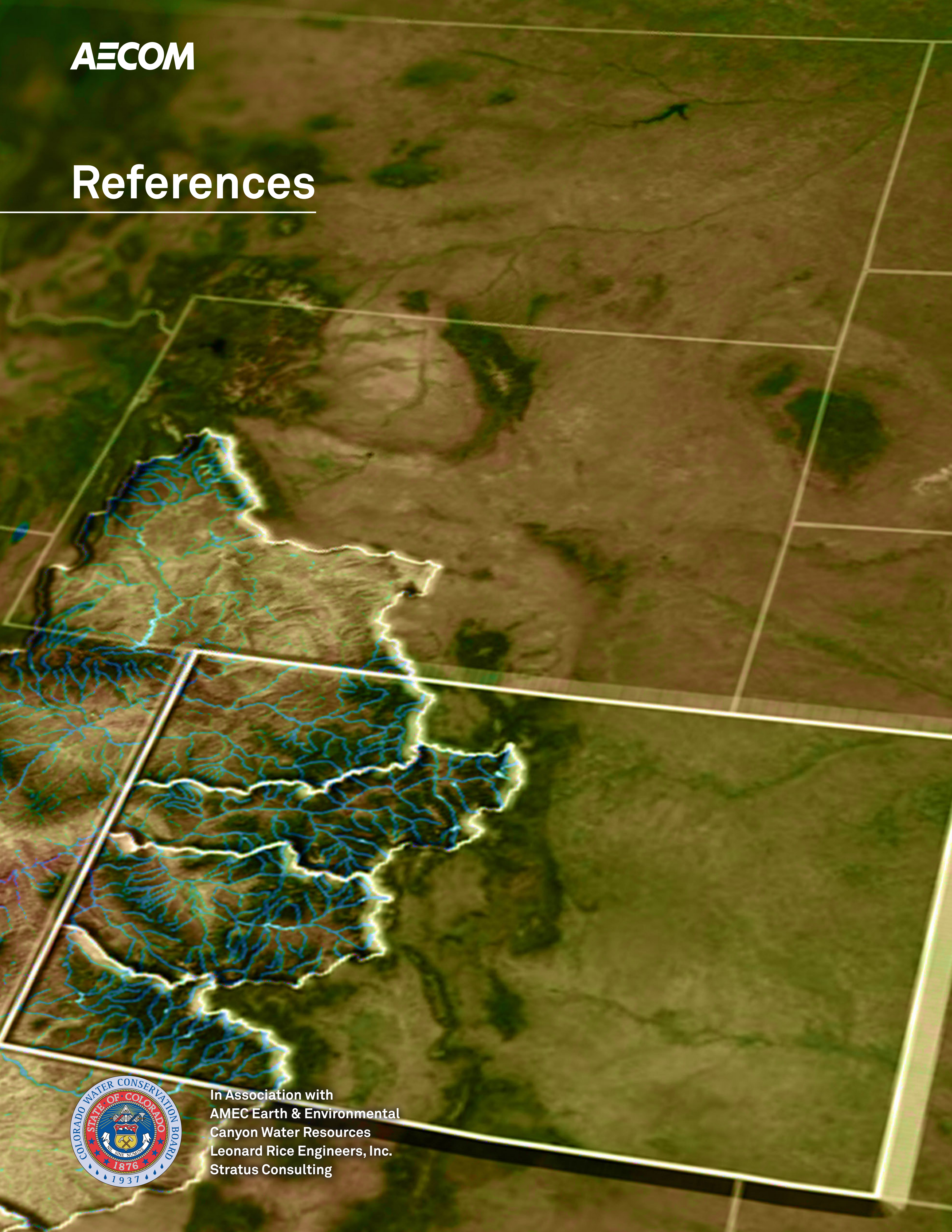
References



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5 REFERENCES

Aguayo, Ingrid. "Bark Beetle Situation in Colorado," Testimony before the Committee on Resources, United States House of Representatives. Hearing on the GAO Report on Invasive Forest Pest. June 21, 2006. http://republicans.resourcescommittee.house.gov/archives/ii00/archives/109/testimony/2006/ingridaguayo.htm

ASCE Manuals and Reports on Engineering Practice No. 70, Evapotranspiration and Irrigation Water Requirements, Edited by Jensen, M.E., Burman, R.D., and Allen, R.G., 1990.

Bosch and Hewlett 1982. "A Review of Paired Catchment Studies for Determining Changes in Water Yield Resulting from Alterations in Vegetation". Journal of Hydrology, Volume 310, Issues 1-4.

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

Christensen, N. and D.P. Lettenmaier. "A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River basin." Hydrol. Earth Syst. Sci., 11, 1417-1434 (2007).

CWCB. Presentation to IBCC. May 17, 2009 U.S. Department of the Interior, "Hydrologic Determination 2007 Water Availability from Navajo Reservoir and the Upper Colorado River Basin for Use in New Mexico. May 23, 2007.

Colorado Water Conservation Board (CWCB), 2010. Colorado Drought Mitigation and Response Plan. September 2010.

Douglass, J. E., and W. T. Swank. 1972. "Streamflow Modification through Management of Eastern Forests. USDA Forest Service, Southeast. Forest Experiment Station Res. Pap. SE-9M-, 15 pp.

Gangopadhyay, S., Harding B., Rajagopalan, B., Lukas, J., and Fulp, T., "A Non-Parametric Approach for Paleohydrologic Reconstruction of Annual Streamflow Ensembles", Water Resources Research, Water Resources Research, Vol. 45, W06417, doi:10.1029/2008WR007201, 2009.

Graham, Russell T., Technical Editor. 2003. "Hayman Fire Case Study." Gen. Tech. Rep.MRS-GTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p. Accessed March 3, 2009.

Hamlet, A.F., and D.P. Lettenmaier. 1999. "Effects of climate change on hydrology and water resources in the Columbia River Basin." Journal of the American Water Resources Association 35(6):1597–1623.

Harding, B. L., Wood, A. W., and Prairie, J. B. 2012. "The implications of climate change scenario selection for future streamflow projection in the upper Colorado River basin", Hydrol. Earth Syst. Sci. Discuss, 9, 847-894, 2012. doi: 10:5194/hessd-9-847-2012.

Hidalgo, H., T. Piechota, J. Dracup. "Alternative principal components regression procedures for dendrohydrologic reconstructions," Water Resources Research. 2000, 36(11).

Hornbeck et al. 1997. Summary of Water Yield Experiments at Hubbard Brook Experimental Forest, New Hampshire. Canadian Journal of Forest Research, 27, 2043-2052.

IPCC, *Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. . Cambridge University Press, Cambridge, UK and New York, NY, 599pp. 2000. http://www.grida.no/climate/ipcc/emission/index.htm.

IPCC, "Third Assessment Report, Chapter 13: Climate Scenario Development. New York, NY, USA, 881pp.

Karl, T. R., Melillo, J. M., and Peterson T. C. (eds) (2009). Global Climate Change Impacts in the United States. Cambridge University Press, 2009.

Liang, S., D. P. Lettenmaier, and E.F. Wood. "One-Dimensional Statistical Dynamic Representation of Subgrid Spatial Variability of Precipitation in the Two-Layer Variable Infiltration Capacity Model." Journal of Geophysical Research. 101.D16 (1996): 21403-21422.

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

Liang, X. Z., Zhu, J., Kunkel, K.E. and Ting, M., (2008). Do CGCMs Simulate the North American Monsoon Precipitation Seasonal–Interannual Variability? Journal of Climate, 21, 4424-4447.

Lin, J. L., Mapes, B. E., Weickmann, K. M., Kiladis, G. N., Schubert, S. D., Suarez, M. J., Bacmeister, J. T., and Lee, M. I., (2008). North American Monsoon and Convectively Coupled Equatorial Waves Simulated by IPCC AR4 Coupled GCMs. Journal of Climate, 21, 2919-2937.

LLNL-Reclamation-SCU, downscaled climate projections derived from the WCRP's CMIP3 multimodel dataset, stored and served at the LLNL Green Data Oasis. 2008. http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/

Lohmann, D., E. Raschke, B. Nijssen, and D.P. Lettenmaier. "Regional Scale Hydrology: I. Formulation of the VIC-2L Model Coupled to a Routing Model." Hydrological Sciences. 43.1 (1998a): 131-142.

Lohmann, D., E. Raschke, B. Nijssen, and D.P. Lettenmaier. "Regional Scale Hydrology: II. Application of the VIC-2L Model to the Weser River, Germany." Hydrological Sciences. 43.1 (1998b): 143-158.

MacDonald, Lee H. and Stednick, John D. "Forests and Water: A State of the Art Review for Colorado." CWRRI Completion Report No. 196. Colorado Water Resources Research Institute. 2003.
http://welcome.warnercnr.colostate.edu/~leemac/publications/ForestandWater.pdf

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

Maurer, E. P., Brekke, L., Pruitt, T. and Duffy, P. B.: Fine-resolution climate projections enhance regional climate change impact studies. Eos Trans. AGU, 88(47), 504 (online at http://www.agu.org/eos_elec/2007/47-504.html), 2007.

Mearns, L. O., M. Hulm, T.R. Carter, R. Leemans, M. Lal, P. Whetton, L. Hay, R. N. Jones, R. Katz, T. Kittel, J. Smith and R. Wilby, 2001: Climate Scenario Development. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom.

Megahan, W.F. and Hornbeck, J. “Lessons Learned in Watershed Management,” USDA Forest Service Proceedings RMRS–P–13. 2000. Accessed January 5, 2009. http://www.fs.fed.us/rm/pubs/rmrs_p013/rmrs_p013_177_188.pdf

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughs, and M.W. Salzer. “Medieval drought in the Upper Colorado River Basin.” Geophysical Research Letters 2007 34(5), L10705, doi: 10.1029/2007GL029988.

Miller, N.L., K. Bashford, and E. Strem. 2003. “Potential Climate Change Impacts on California Hydrology,” Journal of the American Water Resources Association, 39, 771–784.

Mitchell, K.E., Lohmann, D., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Cosgrove, B.A., Sheffield, J., Duan, Q., Luo, L., Higgins, R.W., Pinker, R.T., Tarpley, J.D., Lettenmaier, D.P., Marshall, C.H., Entin, J.K., Pan, M., Shi, W., Koren, V., Meng, J., Ramsay, B. H. and Bailey, A.A.: The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, J. Geophys. Res., 109, D07S90, doi:10.1029/2003JD003823, 2004.

Nakicenovic, Nebojsa, Ogunlade Davidson, G. Davis, A. Grubler, T. Kram, E. Lebre Larovere, B. Metz, T. Morita, W. Perrer, H. Pitcher, A. Sankovski, P. Shukla, R. Swart, R. Watson, Z. Dadi (eds). IPCC 2000: Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York N.Y., Cambridge University Press, 599 pp. 2000. http://www.grida.no/climate/ipcc/emission/index.htm.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp. “A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data.” Water Resources Research 2008 Volume 44, W06423, doi: 10.1029/2007WR006684.

Ray, A. J., Barsugli, J.J. and K. B. Averyt et al. “Climate change in Colorado; a synthesis to support water resources management and adaptation.” A report by the Western Water Assessment for the Colorado Water Conservation Board. 2008.

Reclamation (U.S. Department of the Interior, Bureau of Reclamation). 2007. Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead.

Smith, J. B., Strzepek, K., Rozaklis, L. Ellinghouse, C. and K. C. Hallett. 2009. The Potential Consequences of Climate Change for Boulder Colorado's Water Supplies. NOAA Climate Program Office.

Soil Conservation Service, Irrigation Water Requirement Technical Release No. 21, updated September 1970.

Stednick, John, undated Power Point presentation. "Effects of pine beetle infestations on water yield and water quality at the watershed scale in Northern Colorado," Posted on the Colorado Water Congress web page links. Accessed March 3, 2009. *Microsoft PowerPoint - John Stednick - Effects of Pine Beetle...*

Stockton, C.W. "Long-term streamflow records reconstructed from tree-rings." Papers of the Laboratory of Tree-Ring Research 5. University of Arizona Press. Tucson, AZ. 1975. pp. 1-111.

Stockton, C.W. and G. C. Jacoby. "Long-term Surface Water Supply and Streamflow Trends in the Upper Colorado River Basin." Lake Powell Research Project Bulletin, No. 18, 1976.

Tarawahne, Z. S. and Salas, J.D. (2009). The occurrence probability and return period of extreme hydrological droughts. Proc. Thirteenth Ann. Water Tech. Conf., Hurghada, Egypt., March 12-13, 2009.

US Forest Service and Colorado State Forest Service Release Results of the Annual Forest Health Aerial Survey. The Mountain Pine Beetle, Spruce Beetle and Aspen Decline are Conditions of Concern DENVER, Jan. 16, 2009. http://csfs.colostate.edu/pages/documents/nr_COforesthealth_1-16-09_final.pdf

Walter, I.A., Siemer, J.P., Quinlan and Burman, R.D. (1990). "Evapotranspiration and Agronomic Responses in Formerly Irrigated Mountain Meadows, South Park, Colorado", Report for the Board of Water Commissioners, City and County of Denver, CO. March 1, 1990.

Woodbury, M., Yates, D., Baldo, M. and L. Kaatz. 2012. Joint Front Range Climate Change Vulnerability Study. Water Research Foundation, Denver, Colorado

WCRP CMIP3 Statistically Downscaled Climate Projections. January 15, 2008. LLNL-Reclamation-SCU downscaled climate projections derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. December 15, 2008.

Wood, A.W. and Lettenmaier, D.P.: A testbed for new seasonal hydrologic forecasting approaches in the western U.S., Bulletin of the American Meteorological Society 87:12, DOI:10.1175/BAMS-87-12-1699, 1699-1712, 2006.

Wood, E.F., D.P. Lettenmaier, and V.G. Zartarian. "A Land-Surface Hydrology Parameterization with Subgrid Variability for General Circulation Models." Journal of Geophysical Research. 97.D3 (1992): 2717-2728.

Woodbury, M., D. Yates, M. Baldo and L. Kaatz. Front Range Climate Change Vulnerability Group: A Streamflow Sensitivity Study, Water Research Foundation, 6666 West Quincy Avenue, Denver, CO 80235, in press.

Woodhouse, C. A., S. Gray, and D. Meko. “Updated streamflow reconstructions for the upper Colorado River Basin.” Water Resources Research 2006 42(5), W05415, doi: 10.1029/2005WR004455.

Yapao, P., H. Gupta, S. Sorooshian (1998). Multi-objective global optimization for hydrologic models. Journal of Hydrology, 204(1), pp. 83-97.

Where to find additional references:

The Technical Memoranda prepared for the CRWAS provides additional references. These are available at: http://cwcb.state.co.us.

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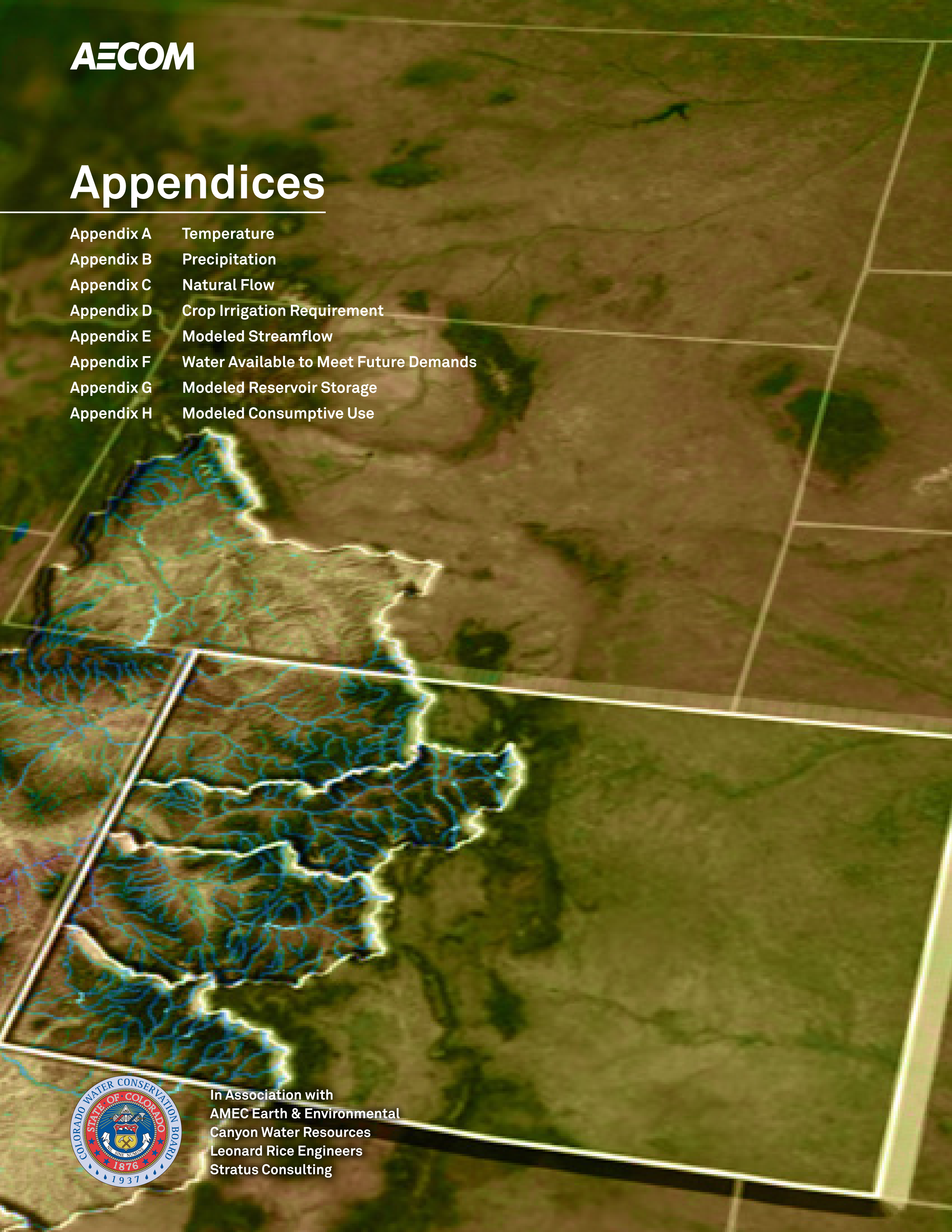
Appendices



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