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Joint Front Range Climate Change Vulnerability Study

Subject Area: Management and Customer Relations

Joint Front Range Climate Change Vulnerability Study

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From its headquarters in Denver, Colorado, the Foundation's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

The results of research are disseminated through a number of channels, including reports, the Web site, Webcasts, conferences, and periodicals.

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Joint Front Range Climate Change Vulnerability Study

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DISCLAIMER

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FOREWORD

The Water Research Foundation (Foundation) is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The Foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the Foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The Foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the Foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The Foundation's trustees are pleased to offer this publication as a contribution toward that end.

Roy L. Wolfe, Ph.D.
Chair, Board of Trustees
Water Research Foundation

Robert C. Renner, P.E.
Executive Director
Water Research Foundation

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We acknowledge the support of the Missouri Basin River Forecast Center (MBRFC), the Colorado Basin River Forecast Center (CBRFC), and the Arkansas-Red Basin River Forecast Center (ABRFC), which provided data and hydrologic models used in their calibration and operational forecast systems for use in this study.

We acknowledge the gridded 1/8th degree data as a primary source of climate forcing data for the WEAP model (Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, 2002).

Special thanks go to Chris Anderson, formerly with the Western Water Assessment and now at Iowa State University, who was key in climate scenario selection and presentation. Special thanks also go to regional experts who helped the group come up with a defendable yet understandable approach, including Brad Udall, Joel Smith, Ben Harding, Levi Brekke, David Raff, Balaji Rajagopalan, Joe Barsugli, and Jessica Lowrey

EXECUTIVE SUMMARY

The Joint Front Range Climate Change Vulnerability Study has been a collaborative effort between water utilities along Colorado's Front Range, the Colorado Water Conservation Board, the Western Water Assessment, the Principal Investigators, and the Water Research Foundation. It has focused on developing and applying procedures for combining the results of the latest climate science with the best available hydrologic simulation capabilities to gain insight into future streamflow trends that could be expected under possible climate change. The collaborative approach allowed participants to identify and support a common assessment methodology, develop a coordinated set of evaluation tools, and combine and efficiently utilize resources rather than pursuing independent, duplicative and more costly studies. An educational component was included and has been essential to developing the methodology, interpreting the results, and understanding needs for future research and investigation. Although the study results indicate broad variability and uncertainty about future streamflow, the results are consistent with the variability and implicit uncertainty associated with the results of the climate models that were used as inputs. The specific findings of this study point toward future research that will improve estimates and enhance understanding of streamflow response to climate change.

OBJECTIVES

The primary objective of this study was to analyze the sensitivity of streamflow to climate change for three watersheds in Colorado and to develop streamflow sequences that represent the effects of projected climate change on a baseline streamflow. This study assesses climate change by comparing average climate conditions between two periods, which may be referred to as a "Delta" approach. Two future time periods were assessed using available climate model outputs to support near-term as well as long-term planning horizons. Each provider will be able to use these future streamflow scenarios in conjunction with its own water rights allocation (water system) model to estimate the impacts of various climate change scenarios to its current and future water supply. In addition to the climate adjusted streamflows, the output of this process is a variety of tables and graphics describing the characteristics of the streamflow response to projected climate change.

A second objective was to bring project participants together to collaborate on this study. Potential benefits of the regional collaboration include resource sharing, coordinated agreement on a study approach, development of a set of evaluation tools that can be applied throughout the region, development of consistent hydrology data available for future planning efforts, utilization of regional experts to educate the participants and ensure a scientifically robust approach, and opportunities for participants to continue working together on climate change planning. This model can provide an example for other regional collaborations.

BACKGROUND

Colorado's Front Range Metropolitan water providers are concerned about the impact climate change may have on future water supply. Depending on the direction, timing, and magnitude of future temperature and precipitation changes, the volume of water available could increase or decrease. Additionally, peak runoff timing could change, possibly leading to water rights complications or the need for operational changes for water utilities that depend on snowmelt for water supply. To better understand the possible impacts of climate change, several Front Range providers are working together to establish the education, tools, and methodology needed to study these potential effects. This project was designed to enable entities that obtain water from the upper Colorado, South Platte, Arkansas, Cache la Poudre, St. Vrain, Boulder Creek, and Big Thompson River Basins to examine the potential effects climate change may have on these supplies. This study involved a complex integration of climate model analysis, water accounting, and hydrologic modeling.

Traditional approaches to water supply planning use historical streamflow records to simulate the operation of existing and planned water supply systems and to evaluate system reliability for meeting current and forecasted demands. This approach considers the climate to be dynamic only to the extent that variability is represented in the observed record, and assumes that discharge patterns will be stationary according to the historic record. Until recently, variability and changes in climate statistics typically have not been explicitly integrated into water resources planning processes. As climate science improves, it enables another element to be included in water supply planning – the effect of projected climate change on streamflow. One source of information that offers insight into climate impacts on future water supply is the output from global climate models (or general circulation models [GCM]) used to project the impact of greenhouse gas emissions on global climate. The study participants, in conjunction with expert guidance, identified an approach for selecting climate model runs and a method for adjusting inputs to hydrologic models based on the climate models. The hydrologic models, in turn, project the streamflow that would result under the selected climate change conditions, indicating the sensitivity of streamflow to climate change.

APPROACH

The approach taken to assess the sensitivity of streamflow to climate change was to:

- Select specific climate projections representative of the range of outputs from multiple climate models;
- Identify a climate change "signal" (the change in temperature and precipitation between a reference period and a selected future period) from each model;
- Apply that climate change signal to the historical inputs for two hydrologic models for the basins noted previously;
- Simulate the hydrologic response from each hydrologic model to produce time series of climate-adjusted natural runoff; and
- Compare the simulation of climate adjusted natural runoff with an unadjusted baseline simulation of runoff to identify potential impacts of climate change.

Applying this approach to the three large-scale river basins of interest to the study participants led to the following four major tasks:

Task 1: Selection of climate model projections

A subset from a catalog of 112 available climate projections was selected to use in the sensitivity assessment. It included five projections of climate for the 30 years surrounding 2040 and five projections of climate for the 30 years surrounding 2070. The five projections were selected to represent the range of outputs of the climate models without extending to the extremes of the results. Qualitative scenario names were given to the projections (for each future period) as follows:

- Hot & Dry,
- Hot & Wet,
- Warm & Dry,
- Warm & Wet, and
- Median.

Task 2: Historical undepleted streamflow data development

Assessing the potential impact of climate change on water supply requires an estimate of the historical streamflow both as a baseline for comparison and also for use in calibrating hydrologic models. Streamflow sequences that have been adjusted to remove the effects of diversions from rivers, reservoir storage, reservoir releases, and agricultural return flows represent the natural streamflow of the rivers and are referred to as *undepleted* flows. The second task of this study was to compile or develop historical undepleted flows for 18 gauge locations of interest.

Task 3: Hydrologic model development

To accurately simulate the impact of climate change on streamflow using a hydrologic model requires a model that properly represents the response of the basin to the climate inputs (specifically temperature and precipitation). In an attempt to distinguish between trends attributable to a fundamental hydrologic response from trends that might be peculiar to a particular hydrologic model, two hydrologic models were selected for use in this study - the Water Evaluation and Planning (WEAP) model from Stockholm Environment Institute (Yates et al. 2005a,b), and the Sacramento model found in the National Weather Service River Forecast System (NWSRFS). The effort began with previously developed historical climate datasets and calibrated hydrologic models, where available, and then updated the model calibrations by adjusting model parameters based on a comparison of model-simulated streamflow and the historical undepleted streamflow at 18 gauge locations distributed among the three watersheds.

Task 4: Assessment of Streamflow Sensitivity to Climate Change

The analysis of streamflow sensitivity to climate change was performed in two stages. In the first stage, a simple sensitivity analysis was used to demonstrate the hydrologic simulation approach and to test the sensitivity of each model and each gauge location to a uniform temperature increase (with no change to precipitation) and to a uniform precipitation adjustment (with no change to temperature). The second stage was to perform a GCM-based sensitivity analysis to assess model response to possible climate change represented by the selected projections in which the temperature and precipitation adjustments vary spatially over the study area and temporally from month to month. In both cases, adjustments were made to the historical climate data inputs to represent climate change, while maintaining the variability associated with the historic record.

To aid in the organization and evaluation of the results of the hydrologic simulations, an automated spreadsheet tool for reviewing and analyzing the results was created. Together, the climate adjusted undepleted flows derived from both the WEAP and Sacramento model simulations for multiple GCM projections represent a sample of possible future streamflow sequences compiled and provided to the study stakeholders. The sequences will allow water resources planners in Colorado to evaluate system responses to a range of possible changes in future streamflow.

STUDY GOALS

As these tasks were identified and defined, specific study goals emerged in an effort to enhance the potential benefits of the study and guide execution of the tasks. The study goals that were identified and achieved as part of the above tasks were to:

- Identify and apply a procedure for selecting multiple climate model projections (Task 1);
- Develop a consistent sequence of historical undepleted flows for the period 1950-2005 (Task 2);
- Develop and calibrate two hydrologic models for use in computing the hydrologic response to temperature and precipitation climate changes. (Task 3);
- Report on the differences in hydrologic model accuracy for water years of differing types, including wet, normal, and dry years (Task 3);
- Test and demonstrate an approach for evaluating hydrologic response to variations in climate using uniform adjustments to temperature and precipitation (Task 4);
- Simulate the hydrologic response to possible climate change in temperature and precipitation by using multiple GCM projections (Task 4);
- Evaluate the hydrologic responses to possible climate change to assess change in runoff volume, timing of runoff, spatial variability of change, elevation impacts, and hydrologic model differences (Task 4); and
- Describe a clear, repeatable procedure for future use in the region or in other parts of the country (documented in this report).

FINDINGS

The pool of 112 GCMs from which 10 scenarios were selected for hydrologic simulation showed broad variability in projected future temperature and precipitation for the North-Central region of Colorado. Though all projections showed warming, the average annual temperature changes ranged from just over 1^{o} to nearly 6^{o} Fahrenheit for the 2040 time period and from about 2^{o} to nearly 10^{o} Fahrenheit for the 2070 time period. Meanwhile, average annual percent change in precipitation ranged from -15% to +17% for the 2040 time period and from -18% to +28% for the 2070 time period (See Table 2.2).

Likewise, there are significant variations in hydrologic responses simulated from the selected GCM projections. For example, average annual change in streamflow volume for the South Platte below Henderson ranges from +33% (Warm & Wet scenario) to -35% (Hot & Dry scenario) for the 2040 period. Analysis of the change in timing for the scenarios considered indicates that the annual runoff could arrive 1 to 14 days earlier in the 2040 simulations and 7 to 17 days earlier in the 2070 simulations.

This range results from the differing average annual changes in temperature and precipitation, from the difference in the monthly distribution of those changes in each projection, and from differences in the spatial distribution of the changes. One of the most important findings of this study is that each climate projection that was considered has a unique impact on runoff volume, and in order to grasp the broad picture of future possible changes in streamflow, the range of impacts from multiple scenarios needs to be considered, as opposed to looking for a central tendency or averages of simulation results. Within this context, the following are key observations drawn from this study:

- GCM model output encompasses a broad range of projected changes to future temperature and precipitation across North-Central Colorado.
- There is substantial variability in projected future streamflow based on the range of climate model projections that were used for streamflow simulation.
- Although the results indicate both increases and decreases in annual streamflow volume, more of the climate projections that were selected resulted in decreases rather than increases.
- Where decreased annual streamflow volume is indicated for a given projection, it is a result of the computed increase in evapotranspiration due to increased temperatures, coupled with either a decrease in precipitation or else a small increase in precipitation that is insufficient to offset the increased temperature effect.
- Where increased annual streamflow volume is indicated for a given projection, it is a result of increased precipitation that is sufficient to offset the increased temperature effect for that projection.
- Spatial and temporal distribution of temperature and precipitation changes across multiple sub-basins and over the twelve-month period has considerable influence on hydrologic model results.
- The two hydrologic models responded similarly to climate change inputs in terms of both annual streamflow volume and timing of runoff.
- At the scale of the river basins evaluated in this study, there does not appear to be a consistent tendency among GCMs regarding elevation-based differences in climate change patterns. Similarly, there are no clear tendencies regarding elevation-based differences in simulated hydrologic response that are evident from the results of both hydrologic models for multiple river basins.
- While increased temperatures are shown to reduce simulated average annual streamflow, the reductions are not uniform across the study area, with the driest basins, such as those in the South Platte, experiencing the greatest percent reduction in streamflow due to warmer conditions, while the wetter basins, including the upper areas of the Colorado, show a smaller percent reduction.

STRENGTHS AND LIMITATIONS IN APPLYING THE STUDY APPROACH

One of the strengths of the overall approach employed in this study is that it allowed a spatial and temporal climate change signal to be incorporated into the hydrologic simulation while preserving the spatial and temporal structure and variability of the historical climate. By selecting specific GCM projections to represent the climate change signal on an average monthly basis instead of using average annual temperature and precipitation adjustments, the results of this study highlight the range that can result from particular combinations of monthly distributions of temperature and precipitation change.

Several limitations in the application of the study approach became apparent over the course of the investigation. First, the study approach does not provide any insight into the potential for increased or decreased intensities of rainfall outside of the average monthly change, or for variation in the diurnal distribution of temperature increases, or for any other characteristic of the GCMs that may indicate fundamental changes in climatic characteristics beyond the average monthly change in temperature and precipitation. This was not a serious limitation for the purposes of this study, but might be important in areas where changes in peak flows are of greater interest. Any efforts to overcome this particular limitation would have to overcome the lack of GCM output available in a format that would support more detailed analysis and would have to be justified with confidence that the climate models are in fact capable of representing those changes in a meaningful way. Second, while perhaps the most important element in determining changes in annual runoff volume is the simulated response of evapotranspiration (ET) to temperature change, there are additional variables beyond temperature that influence ET that were not part of the downscaled GCM outputs and could not be incorporated into the study approach.

LESSONS LEARNED

Two primary considerations in assessing future water availability for Front Range water providers are average annual volume and the timing of runoff. Because the water supply for these agencies is primarily stored in the snowpack, permanent changes in the timing and volume of this important resource would have major impacts on water availability and could force changes in water management strategies. The change in annual runoff volume and timing of runoff are the outputs of the study of greatest interest to the study participants and their constituents.

Runoff timing is most sensitive to temperature, due to its effect on the form of precipitation (rain or snow) and on snowmelt. Precipitation changes alone have a minor influence on runoff timing as shown in the figure on page 68. Even changes in the timing of precipitation have little impact on runoff timing, because of the dominance of snowmelt in the annual runoff cycle, and the controlling impact of temperature on snowmelt. Because all of the climate scenarios indicate increased temperature, nearly all of the scenarios simulated indicate earlier runoff, with the effect being more pronounced in the 2070 period. While the range of projections regarding the number of days earlier that runoff will occur is broad, the tendency to earlier runoff is uniform.

Simulated runoff volume is sensitive to both precipitation and temperature change. The sensitivity to temperature change is because of the influence of temperature on ET in the hydrologic model formulations. Because all of the climate scenarios indicate increased temperature, all of the climate-adjusted runoff simulations are impacted by an increase in ET and a corresponding reduction in volume. Many of the climate projections show a slight increase in precipitation, which partially or wholly offsets the reduction in runoff caused by increased ET. Those projections that show reduction in precipitation accentuate the reduced runoff volume resulting from increased temperature. The occurrence of both increases and decreases in precipitation accentuates the spread of volume changes simulated from the selected climate scenarios.

Based on these observations, study participants may wish to prepare for the impacts of climate change on water availability with the following considerations:

- Expect runoff to occur earlier.
- Consider contingency plans for both increases and decreases in average annual runoff.
- Monitor evolving indicators of climate change at both global and regional scales to identify trends.
- Broaden the scope of selected climate models to use in hydrologic simulation to more fully explore the range of impacts on streamflow.
- Be prepared to incorporate updated climate model outputs in planning processes based on forthcoming advances in climate science.
- Encourage advances in climate science that will facilitate accurate hydrologic assessment.

Climate adaptation is about preparing for change and new conditions in the future. This study provides important information to water utilities and managers to aid in identifying and assessing the hydrologic response to possible climate change.

APPLICATIONS FOR WATER UTILITIES

The methodology of GCM selection, development of adjusted historical climate sequences, and hydrologic simulation developed in this study can be widely applied to assess climate impacts on water supplies both for additional projections in the basins studied or for other locations where there is access to downscaled GCM datasets. Although applying this methodology does not require a thorough understanding of climate science, users of the methodology should be informed about the capabilities and limitations of climate science and models. An important application note is that because of the uncertainty in all of the climate models, it may be valuable and important to simulate water systems operations using multiple climate projections to reveal potential vulnerabilities specific to the hydrologic response to each projection, as discussed in the findings beginning on page 97 .

Finally, it is important for the water utility community to communicate its needs regarding developments in climate science and required outputs from the models to the climate research community so that future efforts might evolve towards methods and information most helpful in understanding and assessing local hydrologic impacts of climate change.

RECOMMENDATIONS FOR ADDITIONAL INVESTIGATION AND RESEARCH

The findings and lessons learned from this study indicate opportunities to improve understanding of the issues surrounding hydrologic response to climate change. Additional investigation efforts should seek to better understand and assess climate variability, while refining aspects of the procedure that can help to reduce uncertainty, as discussed in the recommendations on page 103. The following specific suggestions for additional investigation and research respond to that objective.

1. Climate Model Investigation and Development – output from climate models formed the basis for the evaluation of changes in runoff volume and timing in this study. In the short term it would be helpful to develop a better understanding of the nature of precipitation projections in climate change modeling, including the degree of confidence that might be lent to them, and potential differences between models in accurately simulating precipitation trends. It would also be helpful to investigate and apply possible methods to extract information from the climate models about changes in inter-annual and daily climate characteristics to better understand impacts of climate change on floods and droughts.
2. Additional Scenarios – This study considered just five scenarios from a dataset of 112 possible projections for analysis for each of two future periods. Using the methods and procedures developed for this study, a subsequent analysis based on a simulation of *all* of the available GCM projections would be instructive to better understand the distribution of variability among the streamflow responses to the GCMs.
3. Demand – In using the results of this study in water system models, methods and procedures could be formulated and applied to simulate the impact to corresponding climate change scenarios on demand as done by CWCB in the Colorado River Water Availability Study.
4. Evapotranspiration – A major factor in projecting reduced average annual streamflow volumes in this study is the simulation of increased ET resulting from warmer temperatures. It would be helpful to work with climate model experts to identify elements of climate models corresponding with variables that impact ET (such as wind speed, solar radiation, and relative humidity), evaluate climate model skill in predicting these variables, and determine the feasibility of extracting this information from climate models and including them in the hydrologic modeling procedure.

Many of the participants in this study began with limited experience regarding climate science, climate modeling, and how climate model outputs might be applied to hydrologic models to gain insight into changes in runoff volume and timing under the influence of climate change. Participation in this study has both broadened and deepened the understanding of the participants, and the study methodologies are developed sufficiently such that many of the suggestions for additional investigation and research noted above should now be more accessible to the participants.

MULTIMEDIA

It was important for the study participants to have access to the complete set of results of the study for subsequent efforts. Because of the large amount of data compiled and generated and the difficulty of presenting all of the results of this study in a report, a spreadsheet was prepared as a repository and display tool for the data generated by the models. The spreadsheet was distributed to the study participants and can be made available upon request to the Foundation.

BENEFITS OF REGIONAL COLLABORATION

Regional collaboration was a key to the success of this project and was a valuable component for a number of reasons. Instead of each participant independently embarking on a study to assess climate change impacts to its individual water systems, the collaborative approach allowed participants to work together to develop the tools necessary for an assessment, agree upon a reasonable set of climate scenarios and time periods to examine, and share both data and financial resources. This was particularly useful for Front Range utilities as their water supplies originate from many of the same sources and collaboration reduced duplication. Furthermore, because many utilities in Colorado plan for the future using historic hydrologic records, there was a common need for a hydrology model to convert GCM projections of temperature and precipitation into streamflow and this further enhanced the benefits of regional collaboration.

Another important benefit to regional collaboration on this study was the ability to draw the interest of the academic, scientific, and research communities. Members from each of these communities participated and advised the research team as the study progressed. A single utility, acting alone, would not likely attract the same attention. This partnership resulted in a strong, scientifically defensible, and rigorously reviewed approach, as well as significantly increasing participants' knowledge base through monthly education session with leading experts in climate, water, modeling, and planning. This model is one that can be continued in Colorado and duplicated in other regions of the country.

RESEARCH PARTNERS AND PARTICIPANTS

Funding and/or technical assistance for this study was provided by the following water utilities and water agencies from the Colorado Front Range:

Participating Water Utilities:

Aurora Water
City of Boulder
Colorado Springs Utilities
Denver Water
City of Fort Collins
Northern Colorado Water Conservancy District

Participating Water Agencies:

Colorado Water Conservation Board (CWCB)
Western Water Assessment (WWA) (technical assistance)

These participants, together with others noted below who joined during the course of the study, provided overall direction for the study and collaborated through participation in educational sessions and regular project meetings.

Additional Participants

City of Westminster
City of Cheyenne Utilities
City of Longmont Utilities

CHAPTER 1
INTRODUCTION

Colorado’s Front Range metropolitan water providers are concerned about the impact climate change may have on future water supply. Depending on the direction, timing, and magnitude of future temperature and precipitation changes, the volume of water available could increase or decrease. Additionally, peak runoff timing could change, possibly leading to water rights complications or the need for operational changes for water utilities that depend on snowmelt for water supply. To better understand the possible impacts of climate change, several Front Range providers are working together to provide the education, tools, and methodology needed to study these potential effects. This project was designed to enable entities that obtain water from the upper Colorado, South Platte, Arkansas, Cache la Poudre, St. Vrain, Boulder Creek, and Big Thompson river basins to examine the potential effects that climate change may have on these supplies. This study involved a complex integration of climate model analysis, water accounting, and hydrologic modeling. Figure 1.1 shows a general map of the study area. The study participants included Aurora Water, the City of Boulder (Boulder), the City of Fort Collins (Fort Collins), Colorado Spring Utilities (Colorado Springs), Denver Water, and the Northern Colorado Water Conservancy District (Northern Water). The following introduction briefly presents the background, objectives, approach, and specific aims of this study to provide the reader with context for the detailed descriptions of the individual study components that follow in subsequent sections of this report.

Figure 1.1 General map of study area

Traditional approaches to water supply planning use historical streamflow records to simulate the operation of existing, planned, and potential water supply systems and to evaluate their reliability for meeting current and projected demands. Many utilities have used tree ring data to extend streamflow records, and some have used re-sequencing techniques to further understand their water system vulnerabilities. Until recently, variability and changes in climate statistics have not typically been integrated into water resources planning processes.

The study participants wanted to understand the possible effects that climate change may have on streamflow, and to be able to represent those changes in the context of historical streamflow sequences. In developing this concept, the participants were working in the context of a larger decision framework that addresses the uncertainty of future climate and that could be repeated by other water providers. The framework consists of four elements (partially adapted from a report titled, "Decision Support Planning Methods: Incorporating Climate Change into Water Utility Planning," [Means et al. 2010]), as follows:

1. Increase understanding of climate science, climate modeling, downscaling, hydrologic response to change, planning with new uncertainties, and future climate research directions.
2. Assess climate impacts on hydrologic response and on the vulnerability of water systems.
3. Integrate vulnerability assessment results into water utility planning processes.
4. Make and implement appropriate decisions for infrastructure, operations, supply and demand investments, and policy strategies.

This study addressed one part of the second element of the framework listed above – the assessment of climate impacts on natural water supplies. One source of information that can be used to gain insight into climate impacts on future water supply is the output from global climate models (or general circulation models [GCM]) used to project the impact of greenhouse gas emissions on global climate. Many of these models were compiled and assessed in the Intergovernmental Panel on Climate Change Working Group 1, Fourth Assessment Report (IPCC 2007). The output of these models included time series of temperature and precipitation used to adjust the inputs to hydrologic models. The hydrologic models were then used to estimate the effect the adjusted temperature and precipitation sequences would have on streamflow. The study's participants, in conjunction with expert guidance, identified an approach (described in subsequent sections) for selecting climate projections to be used for this study and a method for adjusting inputs to hydrologic models based on the output from the climate models.

The primary objective of this study was to analyze the sensitivity of streamflow to climate change for three watersheds and to develop streamflow sequences that represent the effects of climate change on the baseline streamflow. Two future time periods were assessed using available climate model outputs to support near-term as well as long-term planning horizons. The change in annual runoff volume and timing of runoff are the key outputs of the study of interest to the participants. Each provider will be able to use the future streamflow scenarios in conjunction with its own water system model to estimate the impacts of various climate change scenarios to its current and future water supply.

A secondary objective related to this study was to give participants an opportunity to learn about regional climate conditions, current observations, climate science, climate modeling, techniques for downscaling climate model output, hydrologic modeling, and the impact of climate change on streamflow. This second objective was achieved through monthly educational sessions conducted by climate science and hydrologic modeling experts.

This report addresses the specific objectives, methods, and results of the streamflow sensitivity analysis and does not present a detailed discussion of the educational aspect of this study.

APPROACH

The approach presented below combines outputs from climate models with hydrologic modeling to achieve the objective of analyzing the sensitivity of streamflow to climate change as outlined above. The approach taken was to:

- Select specific climate projections representative of the range of outputs from multiple climate models;
- Identify a climate change "signal" (the change in temperature and precipitation between a reference period and a selected future period) from each model;
- Apply that climate change signal to the historical inputs for two hydrologic models for the basins noted previously;
- Simulate the hydrologic response from each hydrologic model to produce time series of climate-adjusted natural runoff; and
- Compare the simulation of climate adjusted natural runoff with an unadjusted baseline simulation of runoff to identify potential impacts of climate change.

Applying this approach to the three large-scale river basins of interest to study participants required several preparatory activities in addition to the steps above, and ultimately led to four major tasks, which are introduced below and described more fully in the *Methodology* section of this report.

Task 1: Selection of climate model projections

The primary objective of this study included developing streamflow sequences that represent a range of potential effects of climate change on natural streamflow. Because there are a large number of climate model projections available to represent possible future climate conditions, and because resources did not permit the processing and analysis of the complete set of projections available from the IPCC, a subset of climate projections was selected to use in the sensitivity assessment.

Ten GCM projections were ultimately selected to represent future climate scenarios. Two future periods were considered, with five GCM projections chosen for each future period. Rather than evaluating and using the direct output from each GCM, a dataset provided by the Bureau of Reclamation was used for this study. This dataset provided access to output from a broad selection of GCMs in a consistent format and spatial resolution, as described beginning on page 10. The first future period selected was a period representing conditions in 2040. Because of the annual variability in climate, which is replicated in the climate models, the 30 years surrounding 2040 (2025-2054) were chosen as representative. The second period was chosen to represent conditions in 2070, and corresponds to the 30 years surrounding 2070 (2055-2084). To capture the range of variability in available model results, the outputs from individual GCMs were selected for input to the hydrology models instead of averaging outputs from multiple

GCMs. The climate change signal for each GCM was defined by the average monthly change in precipitation (percent) and temperature (absolute) from the baseline period (1950-2000) to the selected future period (2040 or 2070). The selected GCMs were chosen to represent five qualitative scenarios that describe the general range of temperature and precipitation change found in the larger set of GCM model results for the two future periods. The naming of these scenarios is as follows:

- Hot & Dry,
- Hot & Wet,
- Warm & Dry,
- Warm & Wet, and
- Median.

All of the ten selected projections show a warming trend, with some warmer than others (leading to the designation of "hot"). The precipitation trend is less consistent, with some projections leaning toward an increase (wet scenarios), and some to a decrease (dry scenarios) in future precipitation.

Task 2: Historical undepleted streamflow data development

Assessing the potential impact of climate change on water supply required an estimate of the historical streamflow for use in calibrating hydrologic models which were used to develop a baseline for comparison with climate adjusted flows. Historical observations of streamflow in Colorado include the effects of diversions from rivers, reservoir storage, reservoir releases, and agricultural return flows. Streamflow sequences that have been adjusted to remove these effects represent the natural streamflow of the rivers and are referred to as *undepleted* flows. The second task of this study was to compile or develop historical undepleted flows for 18 gauge locations of interest.

Task 3: Hydrologic model development

To accurately simulate the impact of climate change using a hydrologic model requires a model that properly represents the response of the basin to the climate inputs (specifically temperature and precipitation). It is assumed that if a hydrologic model has been calibrated to effectively represent historical patterns of runoff in response to historical climatological inputs, then it should be able to accurately simulate the runoff that would occur if those inputs are adjusted to reflect potential climate change, as long as the adjustments do not result in climatological patterns that are far outside of any historically observed year.

In an attempt to distinguish between trends attributable to a fundamental hydrologic response from trends that might be peculiar to a particular hydrologic model, two hydrologic models were selected for use in this study. The hydrologic models used in this study were the Water Evaluation and Planning (WEAP) model from Stockholm Environment Institute (Yates et al. 2005a,b), and the Sacramento model found in the National Weather Service River Forecast System (NWSRFS).

David Yates (co-principal investigator) has contributed to the development of the WEAP model, partially funded through the Water Research Foundation and made available to subscribers free of charge. In addition, it has been used throughout the country by water resource planners for conducting climate change studies. Most notably, Colorado Springs Utilities, through another Foundation project (#3132), has been developing a WEAP application to model its water system.

The Sacramento model has a long history of use in the study region by the National Weather Service (NWS) for both short and long-term operational streamflow forecasting. Each model requires its own representation of the historical climate, which is used to simulate the effects of precipitation and temperature on natural runoff processes.

Hydrologic model development and calibration generally involves the following basic activities:

- Model parameterization, in which the geographic area of interest is subdivided to represent sub-watersheds with their respective areas, physical characteristics, and connectivity.
- Historical climate data development, in which historical climate data are compiled and organized in a format that can be used by the respective models. These data are known as the "forcing" data for the model.
- Model calibration, in which various parameters of the models are adjusted to improve the correlation between observed and simulated runoff.

The approach followed for this task began with previously developed historical datasets and calibrated models, where available, and then updated the model calibrations by adjusting model parameters based on a comparison of model-simulated streamflow and historical undepleted streamflow at 18 gauge locations distributed among the three watersheds.

Task 4: Assessment of streamflow sensitivity to climate change

The analysis of streamflow sensitivity to climate change was performed in two stages. In the first stage, a simple sensitivity analysis was used to demonstrate the hydrologic simulation approach and to test the sensitivity of each model and each gauge location to a uniform temperature increase (with no change to precipitation) and to a uniform precipitation adjustment (with no change to temperature).

The second stage was to perform a GCM-based sensitivity analysis to assess model response to possible climate change represented by specific projections in which the temperature and precipitation adjustments vary spatially over the study area and temporally from month to month. The hydrologic modeling approach required the historical climate time series inputs to the WEAP and Sacramento models to be adjusted according to the monthly climate change signals from each GCM projection. Using the adjusted climate inputs, the hydrologic models generate simulations of climate-adjusted streamflow sequences that can be compared to a baseline sequence to determine the streamflow response to a particular climate change signal.

To aid in the organization and evaluation of the results of the hydrologic simulations, an automated spreadsheet tool for reviewing and analyzing the results was created. Together, the climate adjusted undepleted flows derived from both the WEAP and Sacramento model simulations for multiple GCM projections represent a sample of possible future streamflow sequences that were compiled and provided to the study stakeholders. The sequences will allow water resources planners in Colorado to evaluate system responses to a range of possible changes in future streamflow.

STUDY GOALS

The tasks outlined above were performed with the purpose of achieving the overall objective of analyzing the sensitivity of streamflow to climate change for Front Range water supplies. As these tasks were identified and defined, specific study goals emerged in an effort to enhance the potential benefits of the study and guide execution of the tasks. The study goals that were identified and achieved as part of the above tasks were to:

- Identify and apply a procedure for selecting multiple climate model projections for use in hydrologic simulation (Task 1);
- Develop a consistent sequence of historical undepleted flows for the period 1950-2005 for 18 key gauge locations to use in hydrologic model calibration and as a set of baseline flows for comparing against climate adjusted streamflow simulations (Task 2);
- Develop and calibrate two hydrologic models for use in computing the hydrologic response to temperature and precipitation climate changes. This includes establishing input datasets (i.e., climate-forcing datasets) of historical temperature and precipitation for each hydrology model (Task 3);
- Report on the differences in hydrologic model accuracy for water years of differing types, including wet, normal, and dry years, to assist in understanding the effectiveness of models in reflecting change in runoff in response to climate change (Task 3);
- Test and demonstrate an approach for evaluating hydrologic response to variations in climate using uniform adjustments to temperature and precipitation (Task 4);
- Simulate the hydrologic response to possible climate change in temperature and precipitation by using multiple GCM projections, hydrologic models, and future periods of interest (Task 4);
- Evaluate the hydrologic responses to possible climate change to assess:
    - Change in annual runoff volume,
    - Change in the timing of runoff,
    - Spatial variability associated with these changes,
    - Impact as a function of basin elevation,
    - Differences between two hydrologic models in representing the response to climate change.

  (Task 4); and
- Describe a clear, repeatable procedure for subsequent use in the region or in other parts of the country (documented in this report).

CHAPTER 2
METHODOLOGY

The study methodology incorporates four principal activities or tasks: selection of climate model projections, historical undepleted streamflow data development, hydrologic model development, and assessment of streamflow sensitivity to climate change. The following sections describe the methodology and procedures that were followed for each task in conducting this study. Intermediate results of each task are presented as part of the methodology in this section, while results of this study are presented in a separate section titled *Results and Discussion*.

TASK 1: SELECTION OF CLIMATE MODEL PROJECTIONS

Assessing all available temperature and precipitation information from the currently available GCMs was not the objective of the participants. For many of them, this was their first climate change investigation and the main purposes were to develop an understanding of the science, develop the tools necessary to translate current information into streamflow, and assess the impact associated with a representative range of projections. With a better understanding of the science and assessment tools in place, participants can consider additional GCM projections or other new information as required.

By selecting a subset of GCM model projections to assess, the participants developed an easily repeatable and objective model selection approach. Not all water users across the country have access to or the resources for working with climate change experts and modelers to determine which of the many available GCM runs should be used in their assessments. This approach can be used as a systematic way to consider climate information in planning. To date, there are no widely accepted procedures in place within the scientific community for assigning confidence to, or choosing between, the available GCMs (Tebaldi 2005). The model selection procedure used in this study, therefore, does not assume that any single GCM run is more likely to occur than another. The methodology for selecting between GCM runs and developing adjustments to perturb historical climate inputs included the following steps:

1. Selecting among CO_2 emissions scenarios;
2. Identifying GCM projections for which temperature and precipitation output are available for the selected emissions scenarios;
3. Obtaining downscaled GCM output for the GCM projections identified in step 2;
4. Computing average monthly temperature shifts and precipitation adjustment factors (offsets) between the baseline climate period and each of the two future evaluation periods for the downscaled GCM output obtained in step 3; and
5. Selecting a subset of GCM projections based on the offsets computed in step 4 that represent a reasonable range of possibilities over the study region.

Step 1. Select emission scenarios

The Intergovernmental Panel on Climate Change (IPCC) created a Special Report on Emissions Scenarios (SRES) in 2000 created a suite of socioeconomic scenarios of the future which would reflect different development paths and lead to a range of different greenhouse gas emissions profiles. The scenarios differ in demographic, socioeconomic, and technologic development (IPCC SRES 2000). This study assessed the three most extensively examined emissions scenarios, A2, A1B, and B1. The scenarios represent three possible paths that atmospheric greenhouse gas emission concentrations could follow in the future. These paths include a continued rise in CO_2 emissions with no reduction (A2), a continued rise in CO_2 emissions with a leveling-off by mid-21^{st} century followed by reductions (A1B), and a slight rise in CO_2 emissions through mid century followed by substantial declines (B1). These three emission scenarios were simulated at least once, and in some cases multiple times, by 16 of the developed GCMs.

Step 2. Identify global climate models

Many research institutions worldwide have combined atmospheric, oceanic, land, and ice models to develop GCMs. GCMs are used to simulate past, present, and future global climate conditions. The models produce future projections (as opposed to predictions) based on a number of assumptions and do not imply outcome confidence; rather they reflect the relationship between adjusted inputs and model outputs. The simulations considered here are based on the time-adjusted greenhouse gas emissions scenarios (step 1), with various sets of initial conditions.

While the model projections are in general agreement about trends in future temperature, there is much less agreement about future precipitation. For a given emissions scenario, projected temperature and precipitation changes at the regional level vary significantly across GCMs. Also, there are variations in the output from the same GCM driven by the same emission scenario, but with altered initial conditions. Selecting a single GCM projection for evaluation, therefore, cannot represent the range or the uncertainty in current understanding of future climate trends. A better approach for investigating climate change impacts and adaptation strategies for water managers is to evaluate results of a number of GCM simulations to capture a wide range of model projections. The Program For Climate Model Diagnosis and Intercomparison (PCMDI) at Livermore National Laboratories has assembled an archive of climate model output for the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset served at http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php. A list of the GCMs selected from this archive for consideration in this study, including the associated emissions scenarios, and the specific projections developed for those scenarios, is shown below in Table 2.1.

Table 2.1 Climate models included in the selection set. Numbers under emission scenario columns represent different ensemble runs from particular GCMs and emission scenarios.

#	WCRP CMIP3 Model I.D.	Available Projections			Country
		# A1b	# A2	# B1	
1	BCCR-BCM2.0	1	1	1	Norway
2	CGCM3.1 (T47)	1-5	1-5	1-5	Canada
3	CNRM-CM3	1	1	1	France
4	CSIRO-MK3.0	1	1	1	Australia
5	GFDL-CM2.0	1	1	1	U.S.
6	GFDL-CM2.1	1	1	1	U.S.
7	GISS-ER	1	2, 4	1	U.S.
8	INM-CM3.0	1	1	1	Russia
9	IPSL-CM4	1	1	1	France
10	MIROC3.2(medres)	1-3	1-3	1-3	Japan
11	ECHO-G	1-3	1-3	1-3	Germany
12	ECHAM5/MPI-OM	1-3	1-3	1-3	Germany
13	MIR-CGCM2.3.2	1-5	1-5	1-5	Japan
14	CCSM3	1-4	1-3, 5-7	1-7	U.S.
15	PCM	1-4	1-4	2, 3	U.S.
16	UKMO-HadCM3	1	1	1	U.K.

Columns labeled A1B, A2, and B1 refer to the future SRES scenarios described previously. The numbers in the columns indicate the available ensemble members from a particular GCM and emission scenario. An ensemble member is generated each time a model is started from a different condition. As a result, the time series of model variables (i.e. temperature, precipitation, pressure, etc.) of each ensemble member is different, and each ensemble member is considered a "sample" from which climate statistics may be estimated. In some cases, multiple ensemble members have been developed for a given model and emissions scenario, reflecting differing initial conditions, but only a subset of those were available in the dataset used for this study. The numbering of ensemble members was chosen by individual climate modeling groups before the results were submitted to the CMIP3 archive (Barsugli et al. 2009). For example, the researchers running CGCM3.1 submitted five ensemble members for each of the three scenarios, while the GISS-ER researchers submitted only two ensembles for A2, named 2 and 4. Also shown is the country in which the modeling center that developed the model is based. A total of 112 simulations were identified for evaluation.

Study participants decided early on in the process to use downscaled data instead of direct GCM output. The decision was partially based on the accessibility of the downscaled datasets, which are easy for other water managers to obtain and use, but also because the GCM output was already spatially and temporally formatted to a consistent scale, bias corrected for our region, and translated to a higher resolution.

Step 3. Obtain downscaled data

Downscaling is a generic term used to describe the translation of low-resolution climate model output to higher resolution output using additional physical information to create corrected climate data. Output from different climate models varies in its spatial resolution and in the degree to which a given model can accurately reflect historical values in specific regions. It typically has a coarse spatial resolution with some models representing the entire state of Colorado with just a few grid cells. The 112 climate scenario simulations are too coarse to represent the variable climate across Colorado, but are capable of identifying patterns of broad-scale climate change.

This study did not undertake its own downscaling procedure, but instead made use of bias-corrected and spatially downscaled climate projections derived from CMIP3 data and served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/, described by Maurer et al (2007). These datasets were generated through a spatial interpolation technique made available through the Bureau of Reclamation Technical Service Center, Santa Clara University Civil Engineering Department, and The Institute for Research on Climate Change and its Societal Impacts at Lawrence Livermore National Laboratory. That team statistically downscaled results of the selected GCM projections (Table 2.1) using a percentile mapping technique that substitutes real-world data for climate data while retaining the broad-scale climate change signals (Wood et al. 2004 and Maurer 2007). As part of the procedure the climate model grids were resampled to a regular 2º grid to put the wide variety of GCM grid layouts onto the same scale, and then the climate change signals were interpolated from a 2º latitude-longitude grid to a 1/8º latitude-longitude grid using a monthly time step. The procedure included both a bias correction component (more accurately described as a correction of the entire climatologic distribution) and a mapping onto local climatology that implicitly includes an adjustment for terrain.

For this study, downscaled model output was obtained for all of the GCM projections identified for evaluation. These data provided the framework for selecting GCM projections to be used in the streamflow sensitivity study and provided the data used to adjust inputs to the hydrologic models for the study.

Step 4. Compute offsets

The study approach applies the “delta” method, which compares average climate conditions at one time period with a reference time period known as the baseline. The baseline climate period selected was 1950 to 1999. A fifty-year period was selected for the baseline climate to minimize any biases caused by cyclical physical processes and multi-decadal variability. Although the later part of the baseline includes a slight warming trend towards the end of the 20th century for some locations, it is still a useful baseline for comparison with future periods. It also generally frames the various periods currently used by participants for planning purposes.

The baseline climate period (1950-1999) differs from the baseline streamflow period (1950-2005) described in Task 2: Historical undepleted streamflow data development. This is because the year 1999 is the last year in GCM simulations of observed greenhouse gas emissions and the developed emission scenarios take over in the GCMs after this date, whereas the additional six years associated with the undepleted streamflow period include important events that participants wanted to be included in the hydrologic analysis.

Two future evaluation periods were selected, 2025-2054 (representing potential conditions in 2040) and 2055-2084 (representing potential conditions in 2070), for comparison to the baseline period. These periods were selected for consistency with other regional investigations (Smith et al. 2009), and to meet near and long-term planning horizons of the participants. Additionally, the climate model community recommended against using GCM projections near the end of the 21st century because of reduced confidence in the capabilities of the GCMs to simulate global conditions far into the future. Thirty-year averages were selected for the future periods for consistency with the World Meteorological Organization's definition of an appropriate climate time frame and to further minimize the effects of multi-decadal variability inherent to GCM simulations.

Statistically downscaled data were downloaded for a region that covered the entire study area. Boundaries of the study region were 107.526-104.4375 W and 38.5625-40.5625 N, as shown previously in Figure 1.1. This area is described by a 1/8th-degree grid with 17 rows from North to South, and 26 columns from West to East. Outputs from the grid were averaged over the complete study region for the climate model run selection process, although when the climate model outputs were later applied to the hydrologic models, data at 1/8th-degree grid scales were used.

Next, a monthly temperature and precipitation average was computed for the baseline time period using the obtained downscaled data over the entire study region. That is, all Januarys in the 1950-1999 baseline period for each climate model projection were averaged, then all Februarys, etc. This process was then repeated for the 2040 period and for the 2070 period. From the resulting monthly data, monthly differences were computed between 2040 and the baseline, and between 2070 and the baseline to create a temperature change signal for each of the 112 climate simulations. A similar analysis was completed for precipitation, though percent change was computed instead of absolute change. The computed temperature and precipitation changes are referred to in this study as climate change signals, climate adjustments, or climate perturbations representing 2040 and 2070 potential conditions. This approach was developed with guidance from the participants, Principal Investigators, the Western Water Assessment and other local experts.

Step 5. Select scenarios and associated projections for computing adjustments

The selection of a subset of climate model projections to use to assess hydrologic changes was the final step of this part of this study. Though considering all 112 runs for each time period would provide the greatest amount of information, it would have been infeasible for the participants to incorporate so many different sets of adjusted hydrologic patterns in their own planning. The following procedure, developed in cooperation with a team working on a complimentary study (the Colorado River Water Availability Study) with the Colorado Water Conservation Board, was used to identify a set of five GCM projections for each future period for evaluation.

Figure 2.1 shows the annual temperature and precipitation changes over the entire study region for both considered time frames of all 112 downscaled GCM runs (together with the idealized scenario points that were subsequently selected, as described below, for simulation in hydrologic models). From this scatter plot it was apparent that all model runs considered showed warming, though the magnitudes varied across models and emission scenarios. Precipitation changes, on the other hand, were less consistent for the region evaluated, with nearly half showing wetter and half showing drier conditions.

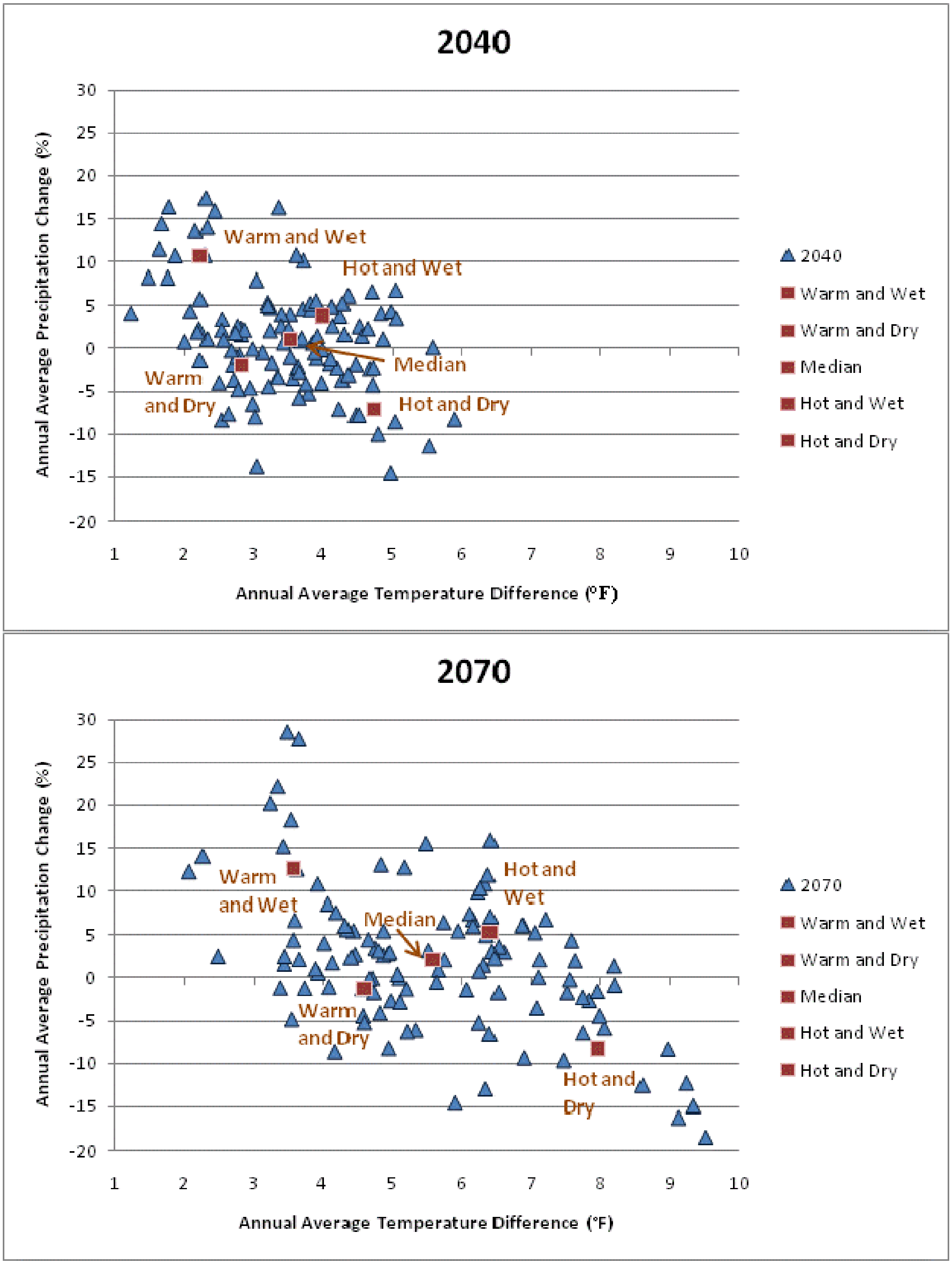


Figure 2.1 Annual Temperature and Precipitation Changes for 112 individual GCMs, with Idealized Qualitative Scenarios as compared to 1950-1999 annual averages. The top graph represents 2040 climate change signals, and the bottom 2070.

The results shown in Figure 2.1 were presented to the participants, and the group chose the following criteria for selecting between the climate model runs:

1. Five scenarios should be selected to represent the corners and middle of the scatter plot;
2. The selected scenarios should represent the general range of the results; and
3. The model selection method should not be biased and should be easy to repeat by other water managers.

Specific GCM runs were then selected as follows: First, five qualitative scenarios were created (criteria 1) to describe the five regions considered. The naming of these scenarios was based on the general observation that all of the projections show a warming trend on an annual basis, with some warmer than others, leading to the designation of "warm" and "hot". Projections for precipitation showed both increases ("wet") and decreases ("dry").

Next, a characteristic value was determined for each qualitative scenario. This step located the qualitative scenario on the scatter plot. The scenarios were intended to incorporate 80% of the annual climate signal spread (criteria 2). The characteristic values were defined as shown in Table 2.2.

Table 2.2 Characteristics of selected five qualitative climate scenarios

Scenario Description	Characteristic Temperature	Characteristic Precipitation
Warm & Wet	10th Percentile	90th Percentile
Hot & Wet	70th Percentile	70th Percentile
Median	50th Percentile	50th Percentile
Warm & Dry	30th Percentile	30th Percentile
Hot & Dry	90th Percentile	10th Percentile

Based on these percentiles, idealized scenario points were plotted on the temperature and precipitation change scatter plot as shown in Figure 2.1.

For each of the two future periods evaluated, a single projection was selected to represent each of the five qualitative scenarios. Ten total projections were ultimately chosen (five for each future period). Actual projections were selected based on their proximity (in terms of Euclidean distance in the T and P dimension space) to the characteristic values for the five scenario points on an annual scale. Five neighbors were selected as candidate projections for each scenario point. One of these five candidate projections was selected based on having a monthly precipitation pattern representative of the mean pattern of the five nearest neighbors. The patterns were assessed according to a root mean square error (RMSE) analysis.

The monthly RMSE analysis was conducted across precipitation patterns rather than temperature patterns because of the large variability in precipitation patterns across each model run. For example, Figure 2.2 illustrates the selection of the National Center for Atmospheric Research's (NCAR) Parallel Climate Model (PCM) driven by emission scenario A2, ensemble 3 (ncar_pcm1.3_A2). The model was the most representative of the mean monthly precipitation percent change pattern in terms of least RMSE of the five monthly projection patterns nearest the Warm & Wet qualitative scenario for the 2040 period. This approach selected the model with the most representative precipitation pattern for the mean of the group of models surrounding the qualitative scenario point.

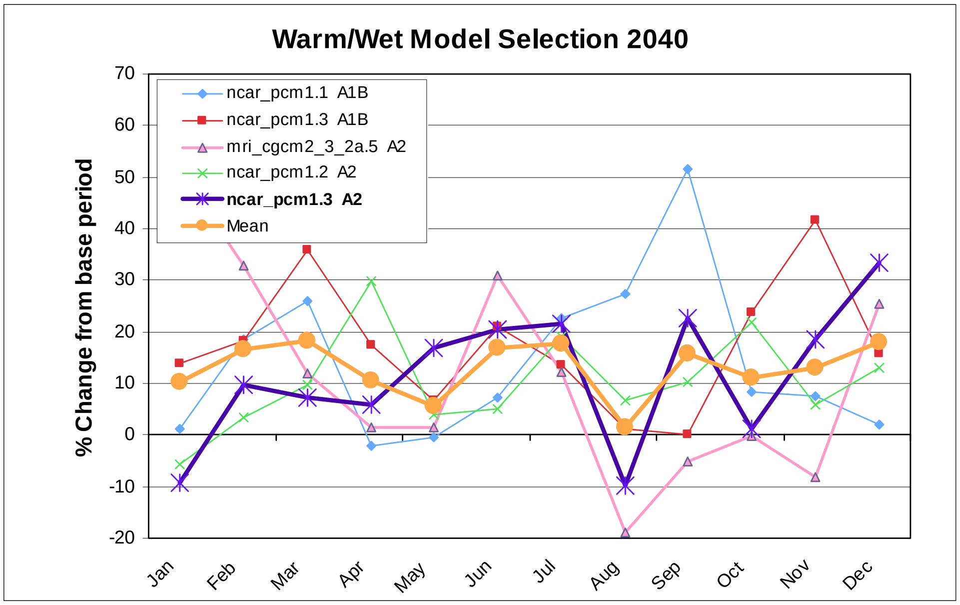


Figure 2.2 Monthly precipitation percent change patterns for five nearest neighboring GCM runs for the 2040 warm & wet qualitative scenario. The NCAR PCM 1.3 model was selected

Figure 2.3 uses the scatter plot to show the resulting climate model runs selected using the procedure described above, as well as the qualitative scenarios for both the 2040 and 2070 periods.

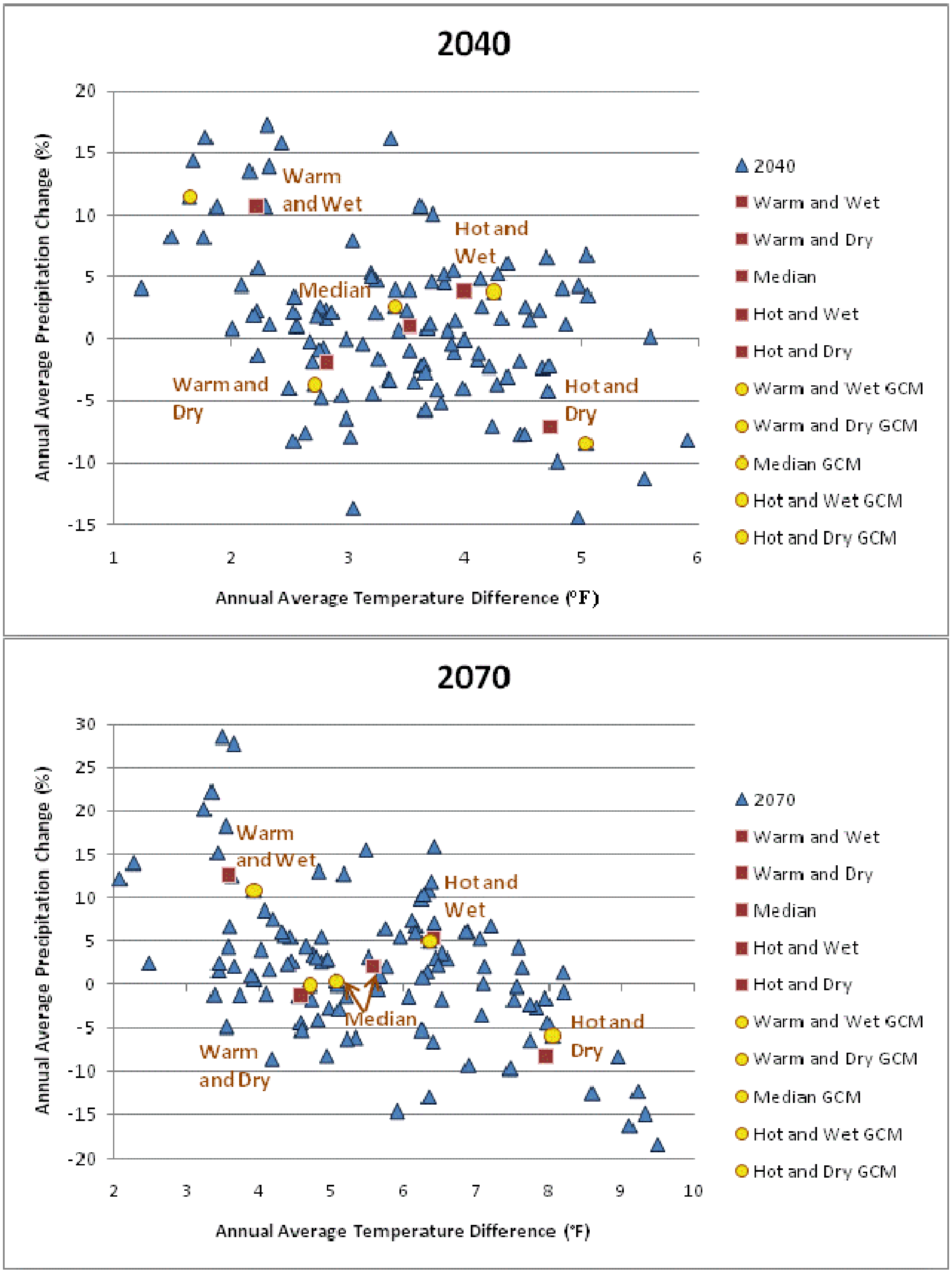


Figure 2.3 Annual Temperature and Precipitation Changes for 112 individual GCMs, with selected model runs and idealized qualitative scenarios as compared to 1950-1999 annual averages. The top graph represents 2040 climate change signals, and the bottom 2070. Red squares represent qualitative scenarios, yellow circles are the selected GCM runs

For simplicity and consistency, the climate models selected are referenced by their qualitative scenario names throughout the remainder of the report (e.g. Warm & Wet).

Table 2.3 and Table 2.4 list the GCM/emissions scenario/ensemble combinations that were chosen to represent each of the qualitative scenarios. For the Warm & Wet and the Hot & Wet scenarios the procedure resulted in the selection of the same GCM/Ensemble and SRES combination for 2040 and 2070. For the remaining three scenarios, a different projection was selected in each period. Average monthly precipitation and temperature offsets were computed for each of these models for each grid point over the study area for use in the hydrologic simulation.

Table 2.3 Year 2040 GCM Model Selection. Temperature and precipitation are average annual changes between baseline and future periods.

Scenario	GCM/Ensemble	SRES	Annual Temperature Increases (°F)	Annual Precipitation Change (%)
Warm & Wet	ncar_pcm1.3	A2	1.64	11.43
Hot & Wet	ncar_ccsm3_0.2	A1B	4.25	3.77
Median	cccma_cgcm3_1.2	B1	3.40	2.60
Warm & Dry	Mri_cgcm2_3_2a.1	A2	2.71	-3.67
Hot & Dry	Miroc3_2_medres.1	A2	5.04	-8.51

Table 2.4 Year 2070 GCM Model Selection. Temperature and precipitation are average annual changes between baseline and future periods.

Scenario	GCM/Ensemble	SRES	Annual Temperature Increases (°F)	Annual Precipitation Change (%)
Warm & Wet	ncar_pcm1.3	A2	3.93	10.81
Hot & Wet	ncar_ccsm3_0.2	A1B	6.35	4.95
Median	mpi_echam5.1	B1	5.06	0.38
Warm & Dry	mri_cgcm2_3_2a.4	A1B	4.70	-0.10
Hot & Dry	gfdl_cm2_0.1	A1B	8.06	-5.90

Figure 2.4 and Figure 2.5 illustrate the average monthly temperature and precipitation change patterns for each GCM run selected to represent the 2040 and 2070 qualitative scenarios, respectively. Monthly temperature and precipitation adjustments based on the selected GCM runs were used to adjust the historical temperature and precipitation datasets used to drive each hydrologic model. This process is explained in more detail in Task 4. Seasonal characteristics of the climate change signals are discussed further in the *Results and Discussion* section of the report.

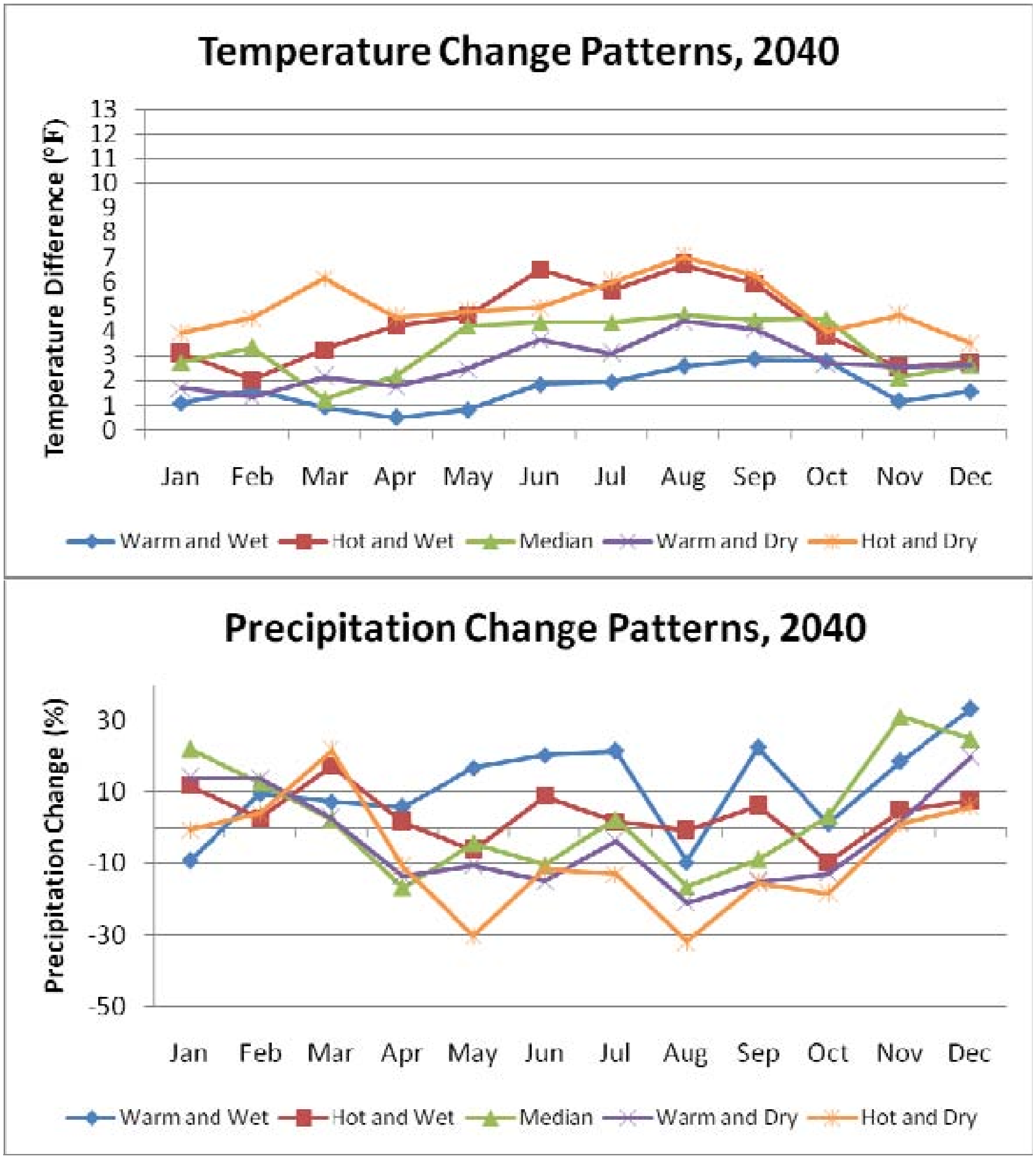


Figure 2.4 Monthly Change Patterns for Temperature and Precipitation, 1950-1999 versus 2025-2054 (2040)

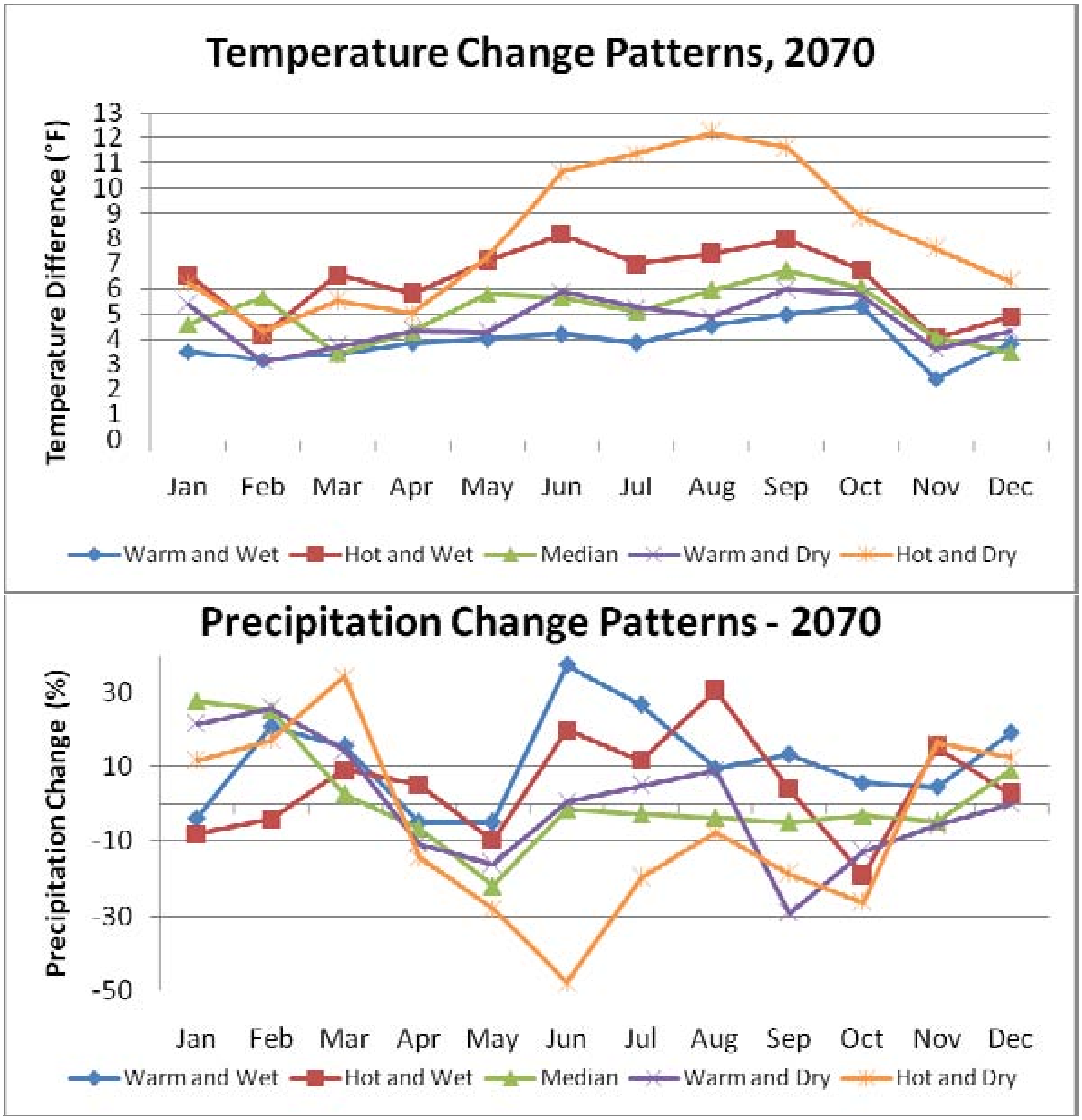


Figure 2.5 Monthly Change Patterns for Temperature and Precipitation, 1950-1999 versus 2055-2084 (2070)

TASK 2: HISTORICAL UNDEPLETED STREAMFLOW DATA DEVELOPMENT

This study included a compilation of undepleted streamflow at eighteen points of interest to the participants: nine points in the Upper Colorado, eight points in the South Platte and its tributaries, and one point in the Arkansas. Undepleted flow refers to the flow that would be observed at a gauging station if the effects of diversions from rivers, reservoir storage, reservoir releases, and agricultural return flows were removed from the observed flows. While undepleted flow is an estimate of naturally occurring flow, it is assumed that some man-made effects, such as changes in water table and changes in land use cannot be accounted for in the undepleted flow calculation, because they are not easily quantified. Estimates of undepleted flow provide a good baseline for assessing the impact of changes in precipitation, temperature, or other factors on the flow available to water users in a basin. All 18 gauging stations are influenced by streamflow regulation at upstream locations, including reservoir storage and release, transbasin imports and exports, and diversions for municipal, industrial, and agricultural uses. The development of historical, undepleted streamflow as part of this study had three important purposes:

1. To have a common set of undepleted flow sequences to use as the basis for calibrating hydrologic models that would be used to simulate the change in hydrologic response due to potential changes in climate;
2. To provide a baseline dataset against which climate adjusted flow sequences could be compared in order to assess the impact of potential climate change; and
3. To give water providers an undepleted flow dataset for use in simulating the operation of existing and planned water supply systems and evaluating their reliability for meeting current and projected demands.

For this study, the period from 1950 through 2005 was used for analysis and evaluation. It corresponds with much of the period used for the climate change analysis (1950-1999), it is a period for which streamflow data are generally available at the points of interest, and it corresponds to the period for which temperature and precipitation data are available for calibration of hydrologic models. Development of undepleted streamflow time series requires careful accounting of diversions, changes in reservoir storage, reservoir surface evaporation, trans-basin imports, and return flows. Prior to this study, the state of Colorado and several of the water providers had developed time series of undepleted streamflow for many of the basins of interest for significant portions of the study period. Developing undepleted streamflow datasets for this study involved the following principal activities:

1. Compiling and reviewing existing historical undepleted flow datasets obtained from project participants and identifying any gaps that may have existed in the datasets in relation to the study period;
2. Evaluating the quality of undepleted flow records and coordinating with project participants to select and agree on the final undepleted flow datasets; and
3. Documenting the undepleted streamflow dataset development process, including the general procedures used in developing the individual undepleted flow datasets from each source, as well as criteria used in selecting the data sources.

A list of the gauges defined for evaluation in this study is presented below in Table 2.5 through Table 2.8. Because it would have been difficult to present detailed results throughout this report for all 18 points, 6 points were selected for which detailed results are presented in subsequent sections in the body of this report. *The six gauges selected are highlighted in bold text in the tables.* They were chosen to represent the three watersheds analyzed in this study and to represent both higher and lower elevation gauges and both headwater areas as well as downstream points. These tables include the watershed's contributing area to the gauge, the undepleted flow in acre-feet, and the undepleted flow per unit area in acre-feet per acre.

Table 2.5 Upper Colorado Undepleted Flow Locations and Data Availability

Basin	Point	Station	Average Annual Undepleted Flow (Acre-feet)	Average Elevation (ft) upstream of point	Contributing area to gauge (1000's of acres)	Avg Ann flow (acre-feet/acre)
Upper Colorado	1	Fraser River at Granby (09034000)	152,000	9,734	190	0.80
	2	Williams Fork near Leal (09035700)	75,500	10,876	57	1.32
	3	Blue River below Green Mountain Reservoir (09057500)	384,000	10,513	383	1.00
	4	**Blue River below Dillon, CO (09050700)**	222,000	10,935	214	1.04
	5	Colorado River near Granby, CO (09019500)	271,000	10,194	207	1.31
	6	Colorado River near Dotsero (09070500)	2,016,000	9,288	2,812	0.72
	7	**Colorado River near Cameo (09095500)**	3,468,000	8,782	5,152	0.67
	8	Homestake Creek at Gold Park (09064000)	43,500	11,295	23	1.89
	9	Roaring Fork River near Aspen (09073400)	109,000	11,252	69	1.58

Table 2.6 Upper South Platte Undepleted Flow Locations and Data Availability

Basin	Point	Station	Average Annual Undepleted Flow (Acre-feet)	Average Elevation (ft) upstream of point	Contributing area to gauge (1000's of acres)	Avg Ann flow (acre-feet/acre)
Upper South Platte	10	**S.Platte River above Spinney Mountain Reservoir (06694920)**	78,000	9,978	463	0.17
	11	South Platte River below Cheesman Reservoir	152,500	9,603	1,114	0.14
	12	**South Platte River at South Platte**	277,000	9,382	1,343	0.21
	13	South Platte River at Henderson (06720500)	517,400	8,322	3,052	0.17

Table 2.7 Upper South Platte Tributaries Undepleted Flow Locations and Data Availability

Basin	Point	Station	Average Annual Undepleted Flow (Acre-feet)	Average Elevation (ft) upstream of point	Contributing area to gauge (1000's of acres)	Avg Ann flow (acre-feet/acre)
Cache la Poudre	14	**Cache la Poudre River at Mouth of Canyon (06752000)**	277,300	8,003	675	0.41
St. Vrain	15	St. Vrain Creek at Canyon Mouth near Lyons	115,300	8,939	138	0.83
Big Thompson	16	Big Thompson River at Mouth of Canyon near Drake (06738000)	123,600	9,588	195	0.63
Boulder Creek	17	Boulder Creek at Orodell	71,200	9,481	65	1.09

Table 2.8 Arkansas Tributaries Undepleted Flow Locations and Data Availability

Basin	Point	Station	Average Annual Undepleted Flow (Acre-feet)	Average Elevation (ft) upstream of point	Contributing area to gauge (1000's of acres)	Avg Ann flow (acre-feet/acre)
Upper Arkansas	18	**Arkansas River at Salida (07091500)**	418,600	10,335	780	0.54

Daily flows were compiled, where possible, for subsequent use in calibrating hydrologic models, although the final results of this study were reported at a monthly time step. The Colorado Decision Support System (CDSS) dataset is derived from monthly records of streamflow, diversions, and reservoir operations. CDSS can disaggregate monthly undepleted streamflow using the daily flow pattern found at nearby gauges that reflect minimal man-made impact, but monthly data are considered more reliable than disaggregated daily data. Monthly undepleted streamflows have been generated for the 1906-2006 period, but the data are more reliable for the years 1975-2005 when there are good monthly diversion records and when daily streamflow records are complete. The advantages of the CDSS data include its availability at many gauge locations, its general acceptance within the state, and that it provides the most up-to-date period of record for recent data.

The Denver Water undepleted daily flow dataset is widely available at many gauge locations, including some for which data are not available in CDSS, and typically extend farther back in time, although data are not available for more recent periods. Data from the recent period of record show the effects of reservoir regulation and might benefit from some data smoothing for future studies.

Data from Northern Water were available only on a monthly time step. Staff from Fort Collins participated in the review and approval process for some of these data. Data were also provided by Boulder and the Colorado Springs Utilities. Figure 2.6 illustrates graphically the availability of the various sources of data.

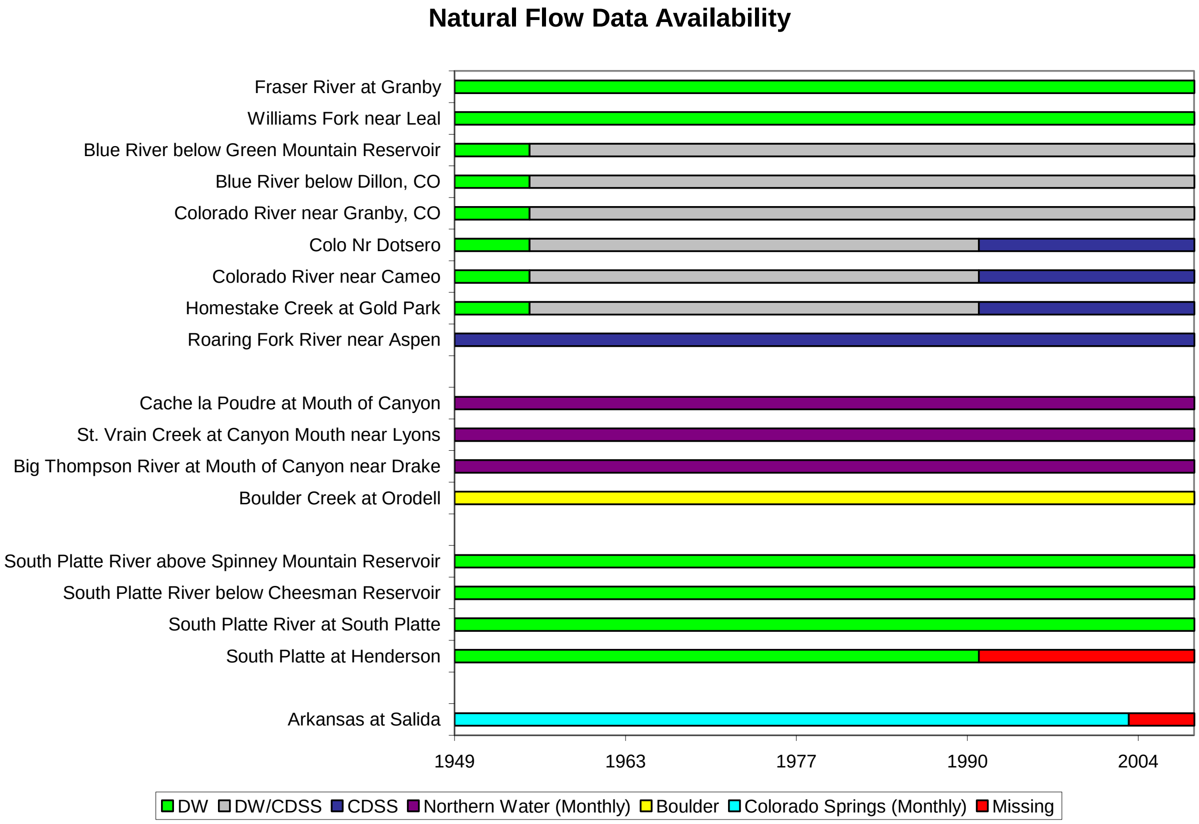


Figure 2.6 Sources of Undepleted Streamflow Data at a Daily Time Step.

Because of its wide acceptance and availability, the CDSS data were used as the default dataset wherever available. At some gauges where the CDSS data overlapped with Denver Water data, a visual inspection of the time series values suggested that for certain months, the Denver Water data were more consistent with the general historical undepleted flow patterns at the gauge. In these cases, the Denver Water data were adopted. Figure 2.7 illustrates a case where Denver Water data were selected in preference to the CDSS data for February, April, May, June, and November for that year. In this figure, the CDSS data (shown in blue triangles) for February, May, and November are inconsistent both with historical monthly values for years not shown, and with preceding and following months for the year shown. In contrast, the Denver Water data (indicated with red circles) show general consistency between months in the year shown and with average monthly values for other years in the historical record.

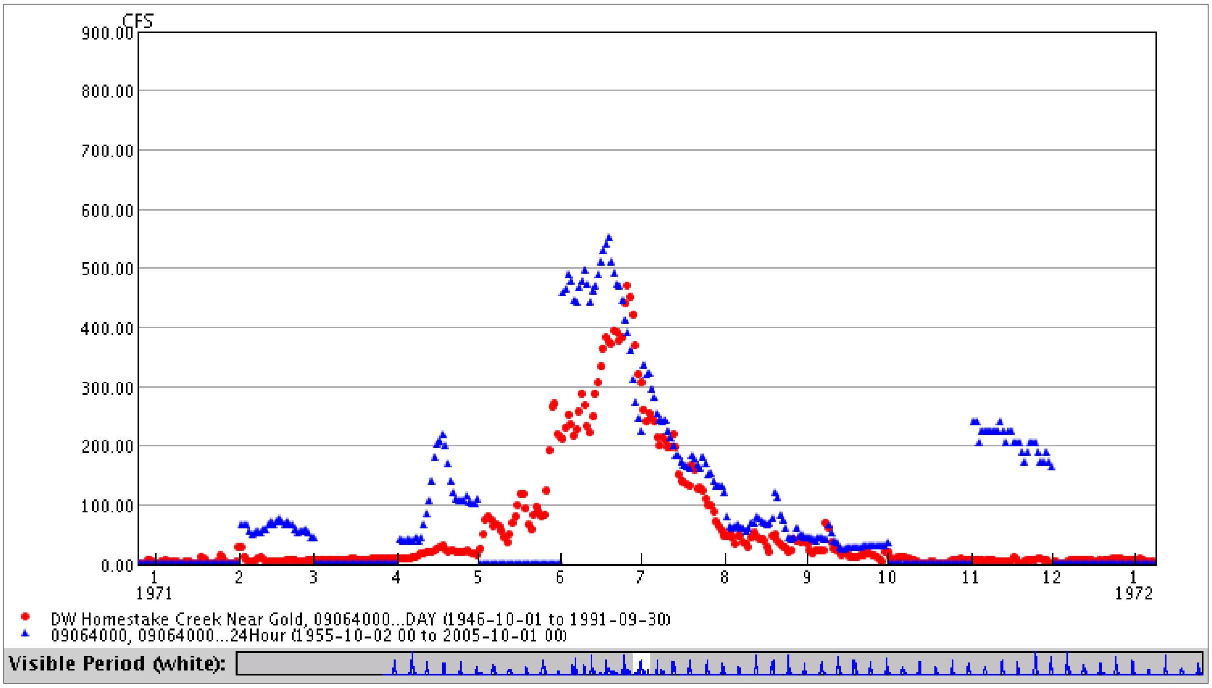


Figure 2.7 Comparison of Undepleted Flow Data Sources at Homestake Creek near Gold Park, 09064000

Colorado Springs Utilities provided a preliminary monthly time series of undepleted streamflows for the Arkansas River (e.g. Arkansas River at Salida [07091500]). In the process of making these calculations, it was noted that some data were missing and it was difficult to reconcile different flow records. Where multiple data sources were available the annual operating plans (AOP) of the Bureau of Reclamation were used, as suggested by Colorado Springs. In some cases, missing diversion data were filled with average monthly values and in some cases where diversion records ended, the diversion was assumed to end as well. Colorado Springs staff noted these challenges associated with the process of undepleted streamflow development for the Arkansas River and indicated a need for additional investigation to improve these estimates.

Annual time series of undepleted flow for the six representative gauge locations are presented in Figure 2.8 through Figure 2.13. Because of the variation in flow magnitude between gages, each of the figures uses an independent scale for flow.

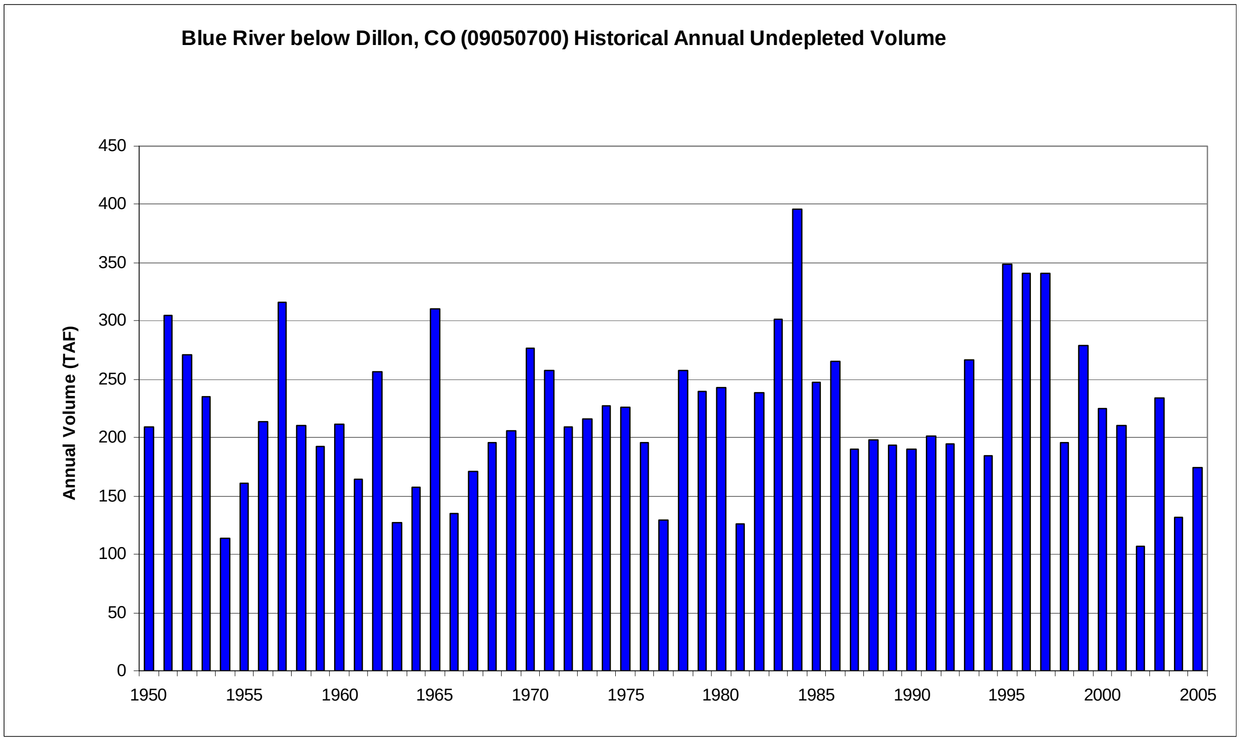


Figure 2.8 Estimated Annual Undepleted Flow, Blue River Below Dillon

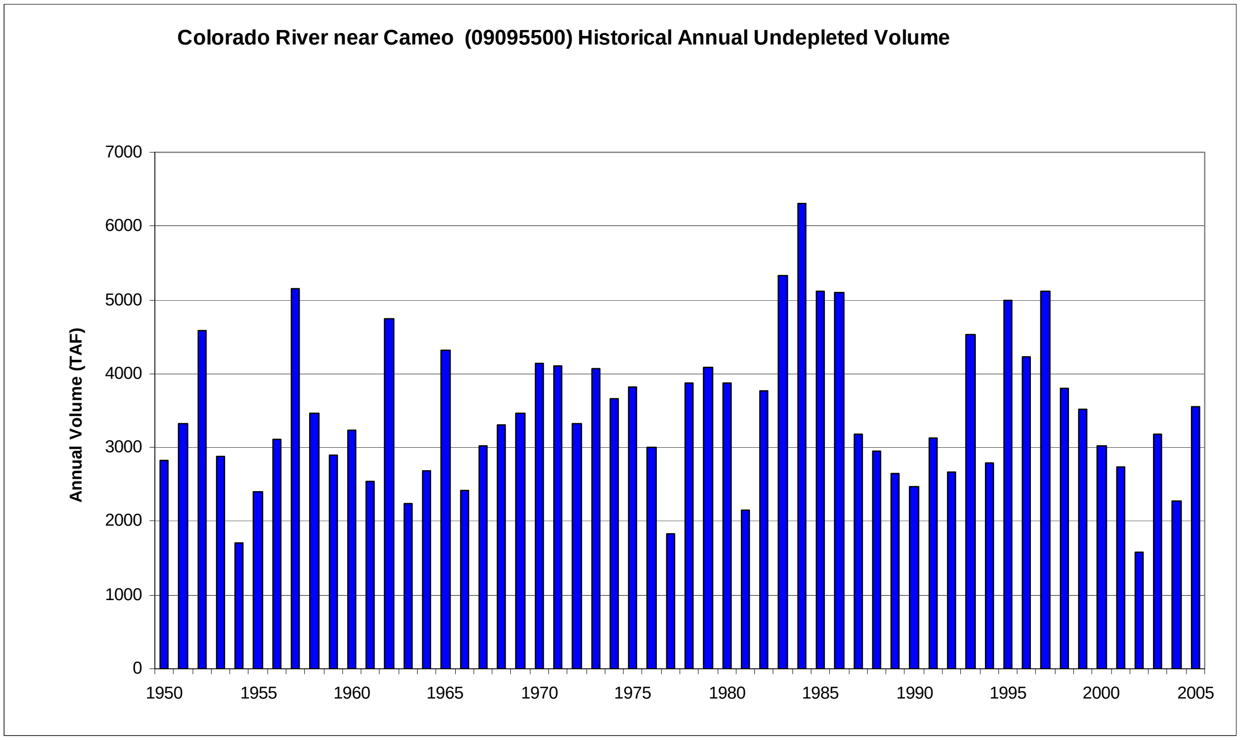


Figure 2.9 Estimated Annual Undepleted Flow, Colorado River near Cameo

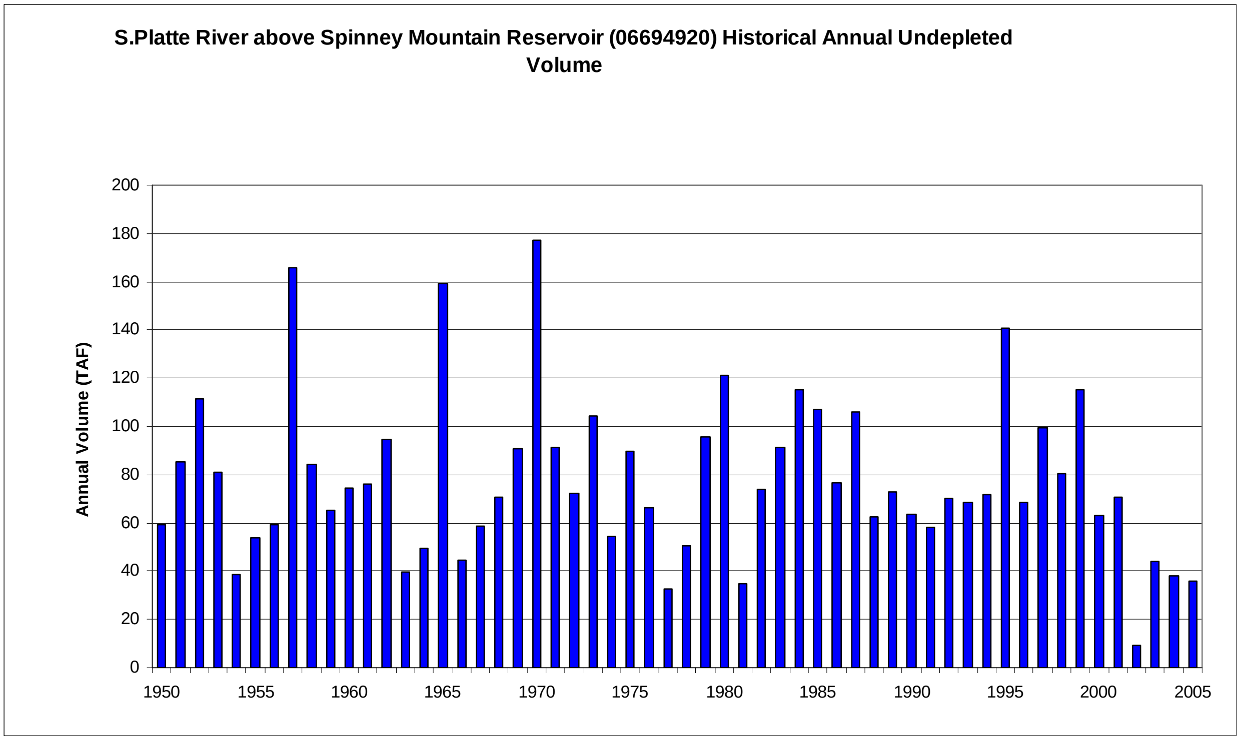


Figure 2.10 Estimated Annual Undepleted Flow, South Platte River above Spinney Mountain Reservoir

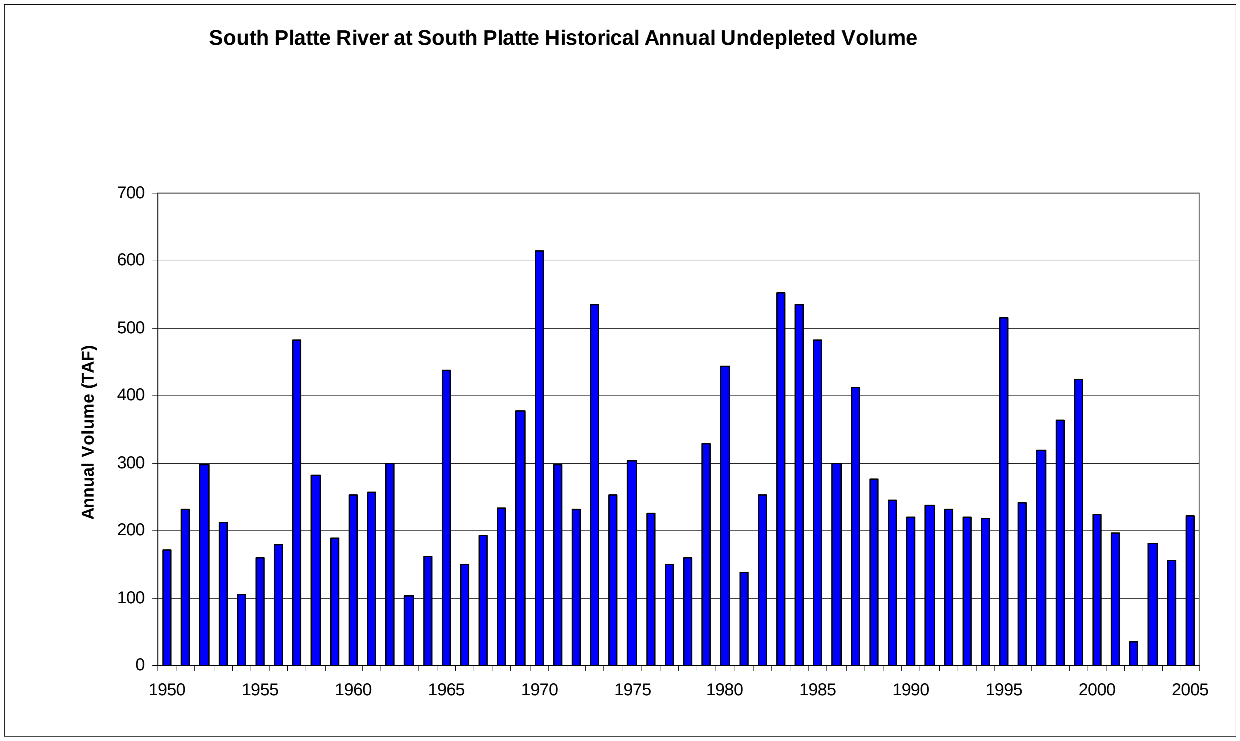


Figure 2.11 Estimated Annual Undepleted Flow, South Platte River at South Platte

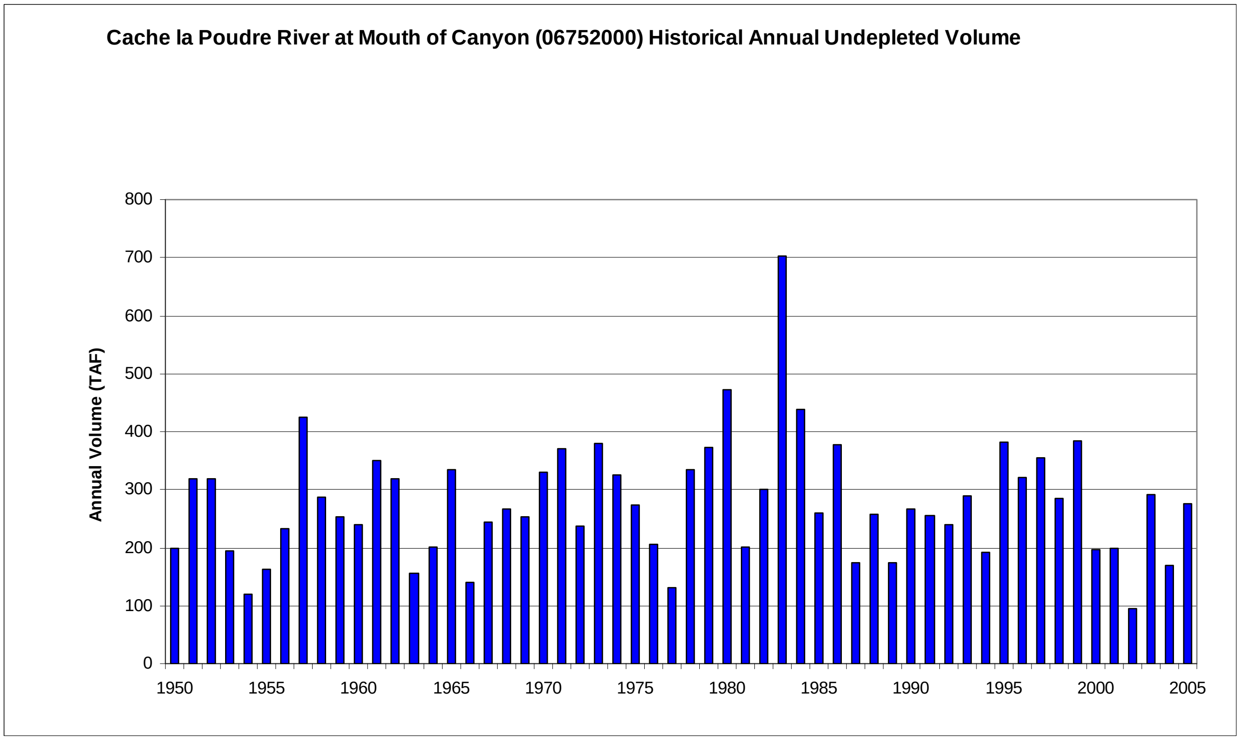


Figure 2.12 Annual estimated undepleted flows for the Cache la Poudre River at the mouth of the canyon

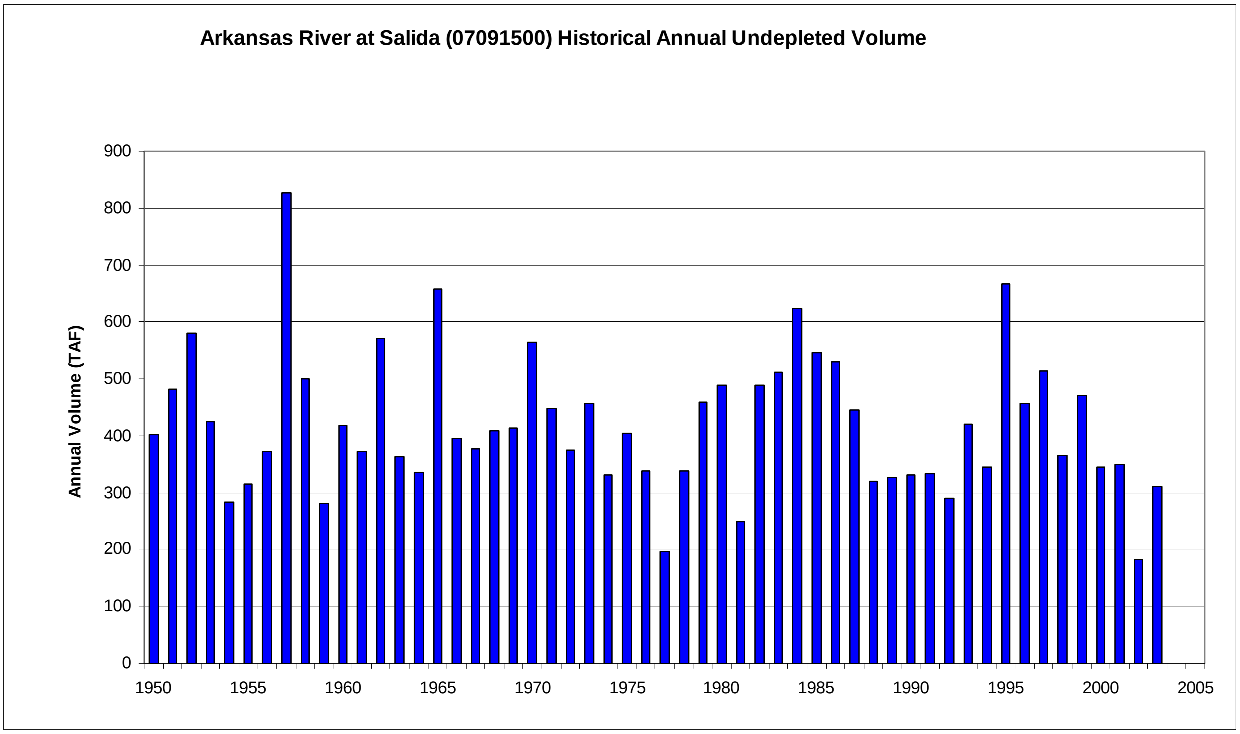


Figure 2.13 Estimated Annual Undepleted Flow, Arkansas River at Salida

Figure 2.6 showed that undepleted flow estimates were not available for some periods for the South Platte at Henderson and the Arkansas River at Salida. As noted previously, the purpose of compiling the undepleted flow datasets was to calibrate hydrologic models, create a dataset to compare against climate change simulations, and for subsequent simulation of water supply system operations. Where there were missing data, the calibration focused on periods with data. For the development of a baseline dataset and for subsequent simulation of water supply system operations, the missing data periods were filled with simulated data from the Sacramento model after its parameters had been calibrated to the available data.

The monthly average undepleted flow for the period 1950 through 2005 was divided by the contributing area (see Tables 2.5 through 2.8), to yield a summary of average monthly flow in units of acre-inches per acre. The resulting data for the six selected gauges are depicted in Figure 2.14. These flow comparisons highlight important differences between the basins. The streamflow generation on the South Platte is quite low relative to all the other basins. The high elevation headwater basins represented by the Blue River below Dillon exhibit higher unit runoff (which is why they are so heavily diverted). The Arkansas Basin shows a slightly later runoff timing than the other basins.

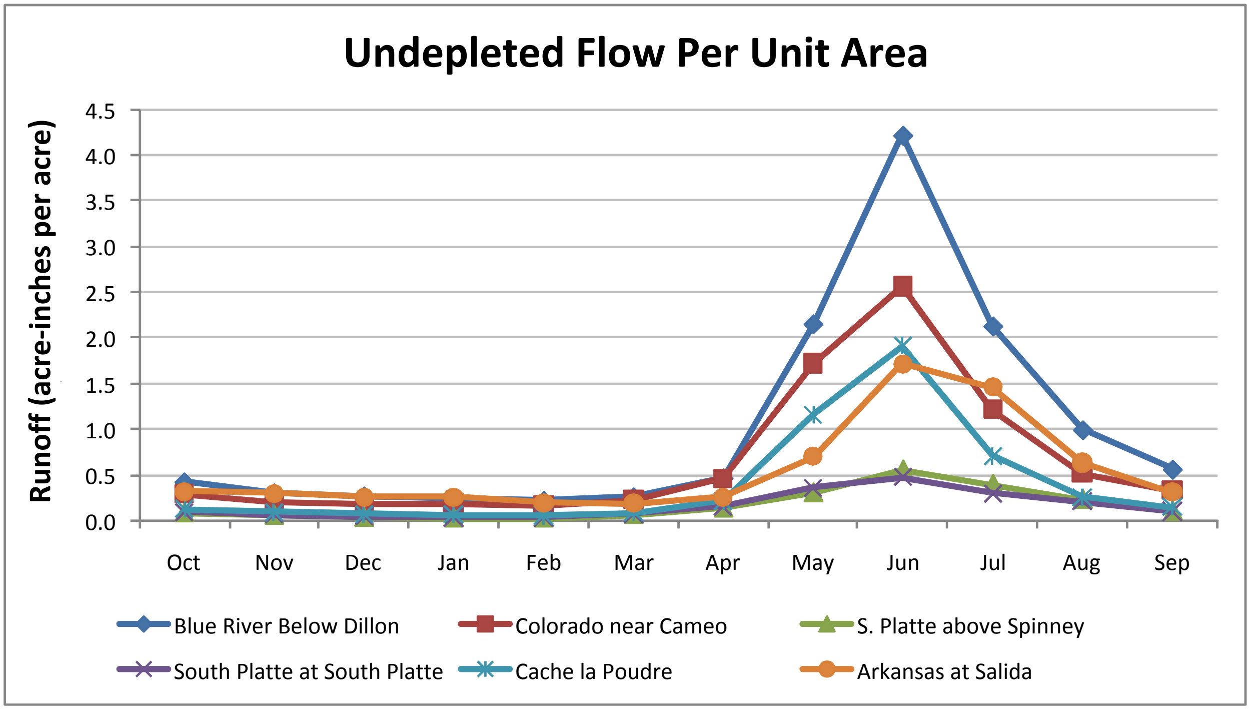


Figure 2.14 Estimated monthly average undepleted flow per unit area

TASK 3: HYDROLOGIC MODEL DEVELOPMENT

As noted in the study approach, simulating the hydrologic impact of climate change requires hydrologic models calibrated to adequately represent historical patterns of runoff in response to climatological inputs. While the intent of this study was to use previously developed historical datasets and calibrated models where available, it was expected that refinement of the calibrations would be required for the models to be consistent with the baseline undepleted flow dataset established in Task 2.

Two independent hydrologic models were configured, calibrated, and applied to assess the relative change in simulated hydrologic response resulting from changes to climate inputs. The selected models were the Water Evaluation and Planning (WEAP) model from the Stockholm Environment Institute (Yates et al. 2005a,b), and the Sacramento model developed by the National Weather Service. Both are conceptual, lumped parameter models that include snowmelt and runoff parameterizations. Overall model attributes are summarized in Table 2.9.

Table 2.9 Summary table showing broad comparison of Sacramento and WEAP models.

Attribute	Sacramento Model	WEAP Model
Time step	6-hourly	Weekly
Topographic Representation	Area-Elevation Curves	1000 foot, banded catchments
Soil Parameters	2 soil moisture zones, water balance solved with mix of discrete and continuous functions	Soil Water Capacity and saturation conductivity, water balance solved as single, continuous formulation
Snow Parameters	Temperature index	Temperature index, radiation based melt-rate
Vegetation	Forest cover and riparian vegetation	Four land classes (urban, forest, non-forest, barren)
Evapotranspiration (ET)	Calibrated monthly Potential ET curve based on Penman Monteith	Weekly Penman Monteith computation based on climate forcing
Historical climate input data	NWS river forecast center time series of mean-areal temperature and precipitation from quality controlled historical climate data	1/8 degree gridded temperature and precipitation mapped to banded catchments (Maurer et al. 2002)

Each model requires a representation of the historical climate (at a minimum, time series of temperature and precipitation) to simulate the effects of climate variability on runoff generation, producing an estimate of undepleted streamflow. Undepleted streamflow is defined as the runoff that would occur in the absence of diversions (including trans-mountain diversions), reservoir storage, and reservoir release. The models were calibrated by adjusting parameters to improve the correlation between simulated streamflow and historical undepleted streamflow developed in Task 2. A summary of each model and its application to the river basins in the study area is presented in the sections that follow.

Sacramento Model Description

In this report the "Sacramento Model" refers to a suite of models used for hydrologic simulation and forecasting by the NWS River Forecast Centers. The specific models used to simulate the impact of climate change in this study are the Snow-17 snow accumulation and ablation model (also known as the Anderson snow model) and the Sacramento Soil Moisture Accounting model (SAC-SMA).

The SNOW-17 model explicitly includes most of the important physical processes that take place within the snowpack. Air temperature is used as the sole index to determine the energy exchange across the snow-air interface, as other climatic variables that impact the snowpack can be reasonably estimated from air temperature. The only other input variable needed to model snow accumulation and melt in the model is precipitation (Anderson 1973, 1976).

SNOW-17 represents the physical processes that occur in a column of snow, but incorporates additional methods to allow application to an area. The main processes included in the model for a column of snow are:

- *Form of precipitation*

  SNOW-17 computes a rain-snow elevation time series and then computes the fraction of the area where rain is occurring and the fraction where it is snowing based on an area-elevation curve.
- *Accumulation of the snow cover*

  SNOW-17 uses a snowfall correction factor, parameter SCF, to adjust all new snow amounts before they are added to the existing snow cover. The temperature of new snow is assumed to be equal to the air temperature or 0°C, whichever is less. When the temperature of the new snow is less than 0°C, the "heat deficit" of the existing snow cover is increased. The "heat deficit" is the amount of heat that must be added to the new snowfall in order to bring it up to a temperature of 0°C.
- *Energy exchange at the snow-air interface*

  The SNOW-17 model calculates the energy exchange at the snow-air interface in different ways depending on whether rain is occurring or not. When sufficient rain occurs, the model uses the energy balance to compute surface melt by making several assumptions:

  - incoming solar radiation is negligible because overcast conditions generally prevail;
  - incoming longwave radiation is equal to black body radiation at the temperature of the cloud layer which should be reasonably close to the air temperature:
  - relative humidity is quite high (90% is assumed); and
  - the snow surface temperature is 0°C (273°K).

When there is no or very light rainfall and the air temperature is above a base value, SNOW-17 uses a melt factor to estimate the amount of surface snowmelt. The melt factor itself varies seasonally between maximum and minimum values that depend on the MFMAX and MFMIN model parameters with units of mm/(^{o}C*6hr).

SNOW-17 uses a heat deficit to keep track of the net heat loss from the snow cover due to energy exchange across the snow-air interface,

- *Internal state of the snow cover*

  SNOW-17 treats the snow cover as a single lumped entity. The model calculates the temperature and liquid water or density profile within the pack. It assesses the overall state of the snow cover by accounting for snow cover ripeness through the snow's heat deficit and liquid water storage.
- *Transmission of water through the snow cover*

  SNOW-17 uses empirically derived equations to calculate the lag and attenuation of water through a ripe snow cover.
- *Heat transfer at the soil-snow interface*

  SNOW-17 includes a daily ground-melt parameter, DAYGM, which is a fixed estimate of the average melt that occurs at the snow-soil interface throughout the period when snow is on the ground.

To apply SNOW-17 to an area, the model must calculate the areal extent of the snow cover. To do so, the model keeps track of average areal values of state variables, energy exchange, and water balance quantities, and adjusts results by the areal extent of the snow cover before computing mean areal values. The areal extent of snow cover is computed as a function of snow depth from the areal extent of snow cover (AESC) curve parameter.

The output of the SNOW-17 model is a 6-hour time series of rainfall plus melt depth over a sub-basin, as well as a time series of the percent of the basin that is snow covered. These time series are used as input to the SAC-SMA model, which ultimately computes the amount of runoff that enters the river drainage network.

The SAC-SMA runoff model parameterizes soil moisture characteristics such that applied moisture is distributed in various depths and energy states in the soil, there are rational percolation characteristics, and that streamflow is effectively simulated. This is achieved by explicitly modeling the following water balance components in a soil column:

- Tension water,
- Free water,
- Surface flow,
- Lateral drainage,
- Evapotranspiration or ET, and
- Vertical drainage (percolation).

The soil column is divided into upper and lower zones, each with its own tension and free water compartments. (See Figure 2.15). The following runoff components are included in the model:

- *Impervious runoff*

  Impervious runoff is derived from rainfall over permanent impervious areas of the basin that drain directly to the stream channel, and is directly added to the channel inflow. It is determined based on the percentage of impervious area in the basin, parameter PCTIM.
- *Direct runoff*

  In the permeable portion of the basin, rainfall (or snowmelt) first enters the Upper Zone Tension Water, which must be totally filled before water becomes available to enter other storage zones. Once this zone is filled, additional impervious areas (determined by parameter ADIMP) can develop and produce direct runoff, which is directly added to the channel inflow. The capacity of the Upper Zone Tension Water is defined by the UZTWM parameter.
- *Interflow*

  Excess water from the Upper Zone Tension Water passes to the Upper Zone Free Water, with some water percolating to deeper soils at a rate controlled by the contents of the Upper Zone Free Water zone and the deficiency of lower zone water volumes. This “percolation demand” is also affected by two model parameters (ZPERC, REXP) that define maximum percolation demand and a reduction exponent, or by an optional module reducing percolation and interflow rates due to frozen ground. Water not percolating to deeper zones can run off as interflow. The SAC-SMA model includes a recession parameter (UZK) which controls the rate at which interflow is produced based on the excess contents of the Upper Zone Free Water.
- *Surface runoff*

  The capacity of the Upper Zone Free Water zone can be defined by the UZFWM parameter). Heavy precipitation or significant snowmelt can fill the Upper Zone Free Water zone, which causes additional water to run off as surface runoff.
- *Short-term and Long-term baseflow*

  Water reaching the lower soil zones is divided between the Lower Zone Tension Water and two Lower Free Water zones based on a parameter called PFREE. Water contained in the Lower Zone Tension Water will not produce baseflow, but is subject to ET. Baseflow is produced from Lower Zone Primary drainage (controlled by parameter LZPK) and Lower Zone Supplemental drainage (controlled by a parameter LZSK). The sizes of the three lower soil zones are defined individually (parameters LZTWM, LZFPM, and LZFSM).

All soil zones are subject to ET. Evaporation demand can be specified in the SAC-SMA model either as mid-monthly averages or as time series. Actual ET (AET) is computed by the model as a function of demand and availability.

Output from the SAC-SMA is a 6-hour time series of total channel inflow and is composed of the sum of the flow components listed above minus losses to groundwater (parameter SIDE) and losses due to ET from riparian vegetation (parameter RIVA). A unit hydrograph model is required to convert the total channel inflow into discharge at the basin outlet. The UNIT-HG model in NWSRFS performs this function.

Figure 2.15 depicts the SAC-SMA soil zones and the conceptual paths of moisture in the soil column.

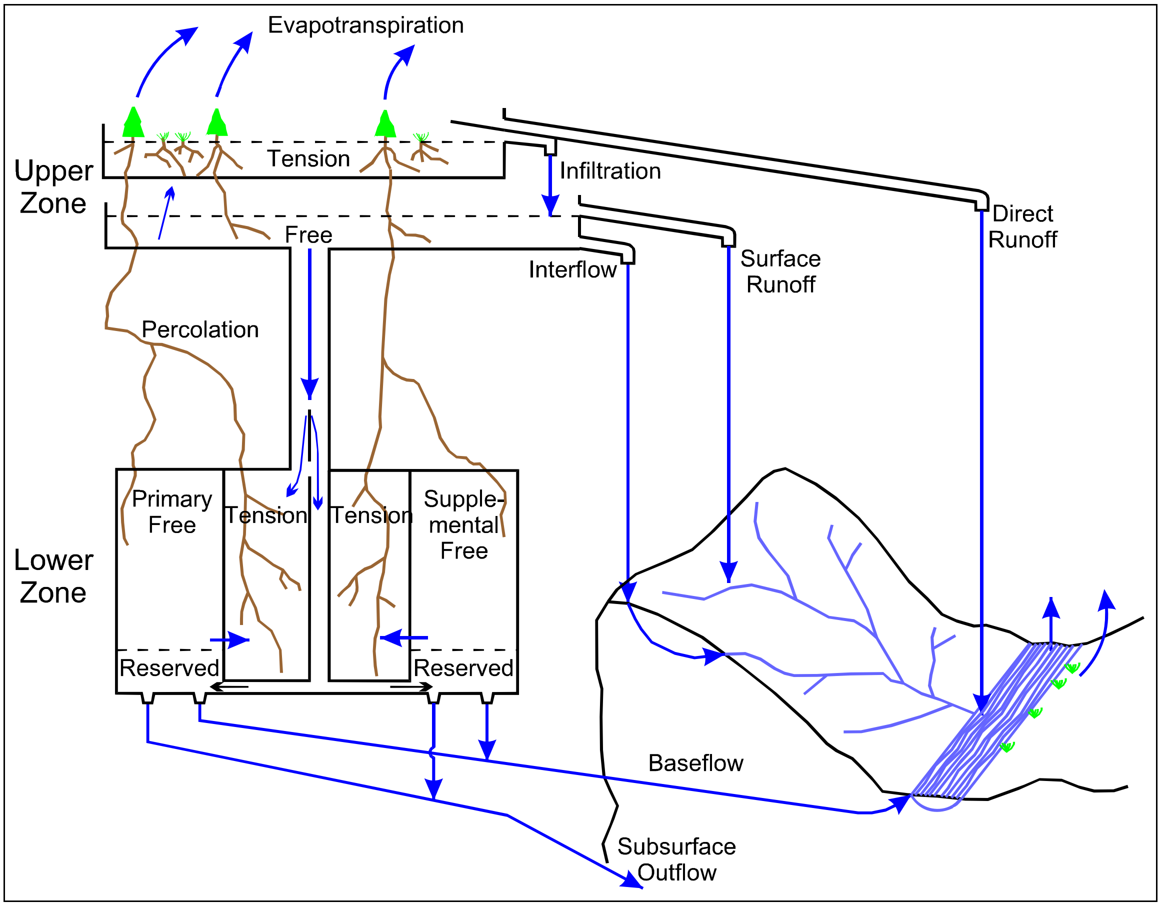


Figure 2.15 Soil Zones of the SAC-SMA model

The SAC-SMA model is capable of estimating runoff for many climate regimes and model configurations. However, the following limitations apply.

- The model's conceptual soil moisture zones are lumped over large areas. Therefore, the model does not account for uneven filling of soil moisture zones during localized events and subsequent local runoff.
- The SAC-SMA does not account for the infiltration capacity of the upper zone. Therefore, it does not accurately simulate situations when very large precipitation rates exceed the infiltration capacity of unsaturated soil and lead to direct runoff.

Because the SNOW-17 and SAC-SMA models are used by the NWS for developing real-time hydrologic forecasts (including flood forecasting), they are designed to be executed at time steps of less than a day (six-hour time steps are most common). Processes that vary at time scales smaller than the defined model time step may not be simulated accurately, while processes of interest at larger time scales, including those of interest to this study, can be adequately represented by accumulating model output to the larger time step.

Sacramento Model Implementation

The Sacramento model was calibrated previously by the NWS for the South Platte, Colorado, and Arkansas River Basins, based on time series of undepleted streamflow that were available at the time the calibrations were performed. One of the purposes of this study was to refine the hydrologic model calibrations based on the undepleted streamflow time series developed in Task 1. The hydrologic models and historical climate data associated with each of the three river basins involved in this study are managed by three different NWS forecast centers and the procedures used in the previous model development and calibration varied among the three river basins.

The hydrologic model configurations used by the NWS River Forecast Centers subdivide the river basins into multiple sub-basins and elevation zones to account for spatial variability in precipitation, temperature, and basin snowmelt and runoff characteristics, as well as to correspond to required forecast points. The historical temperature and precipitation time series developed by the NWS offices for use in model calibration were the same ones used in this study and represent the mean areal characteristics of each sub-basin. The resulting time series are defined at 6-hour time steps.

The locations where undepleted flows have been developed for this study correspond with forecast points in the NWS models, but the NWS models include additional subdivisions of basins upstream of each of the undepleted flow/calibration points used in this study. Figure 2.16 illustrates the calibration points in the Colorado River basin used in this study.

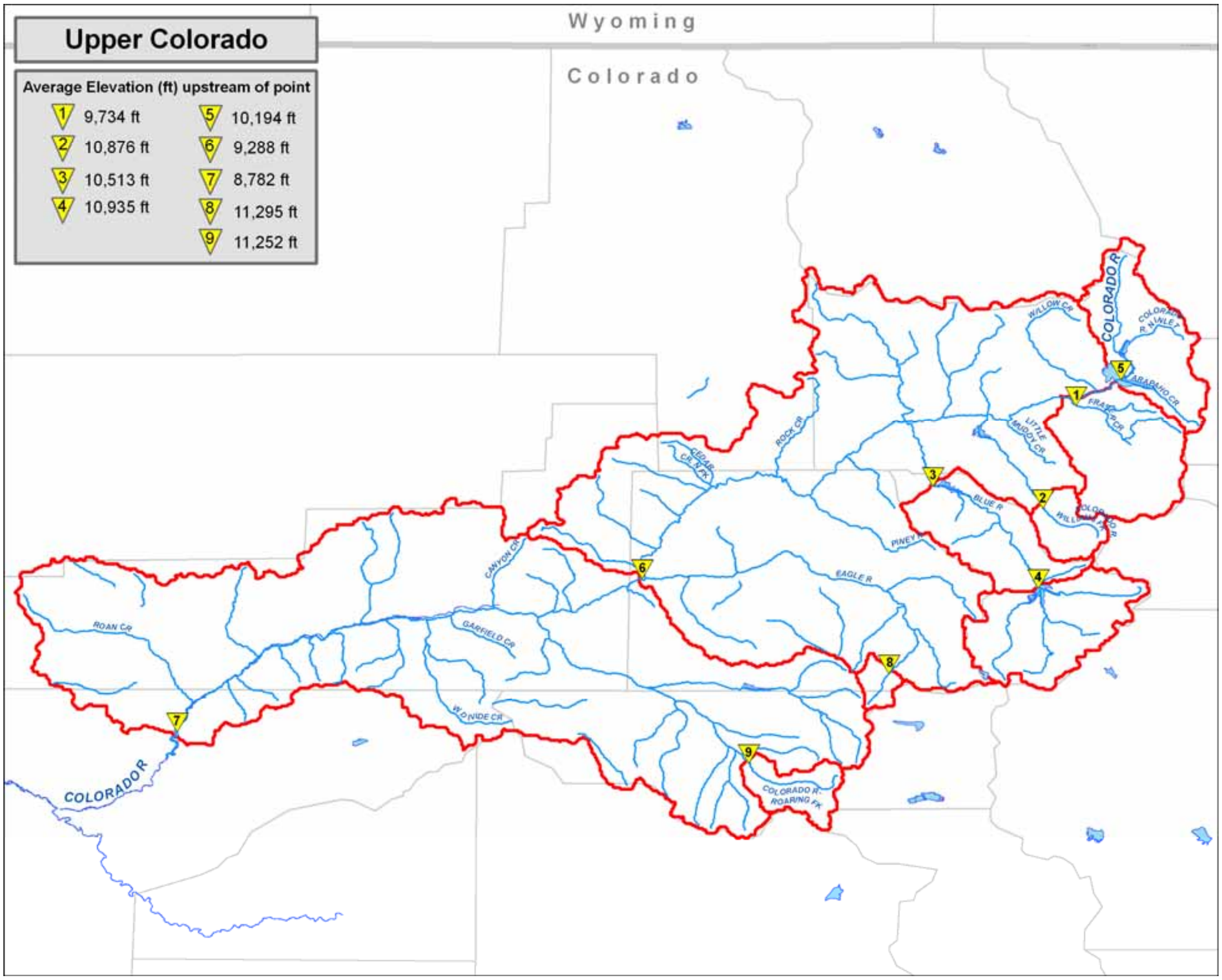


Figure 2.16 Upper Colorado Basin Study Points

The basins are numbered to correspond to the undepleted flow points listed previously in Table 2.5 through Table 2.8. Figure 2.17 and Figure 2.18 show the calibration points in the South Platte and Arkansas River basins. The calibration effort for this study required model parameters in multiple upstream sub-basins and sub-areas to be adjusted in a consistent fashion to meet calibration objectives at downstream points.

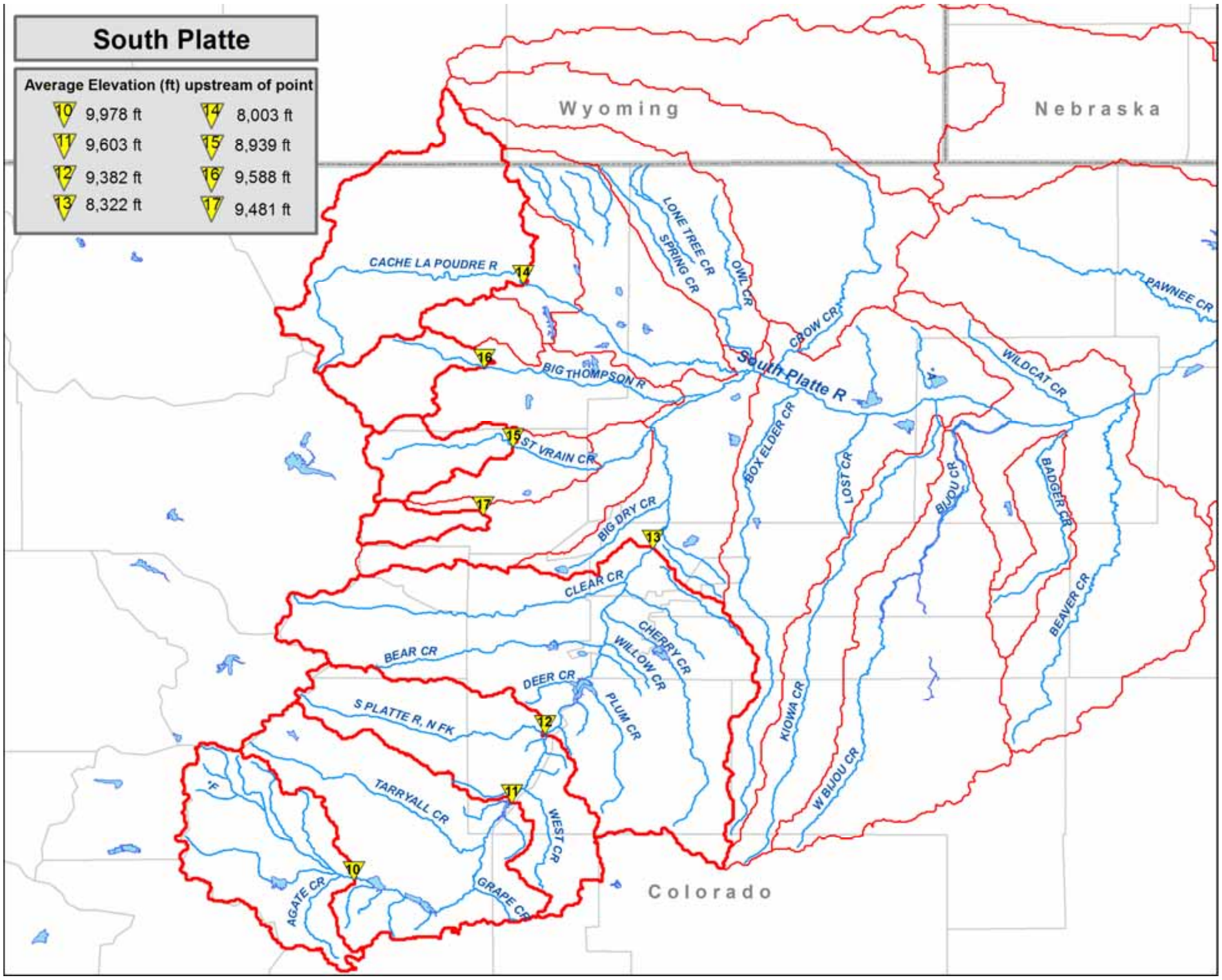


Figure 2.17 South Platte Study Points

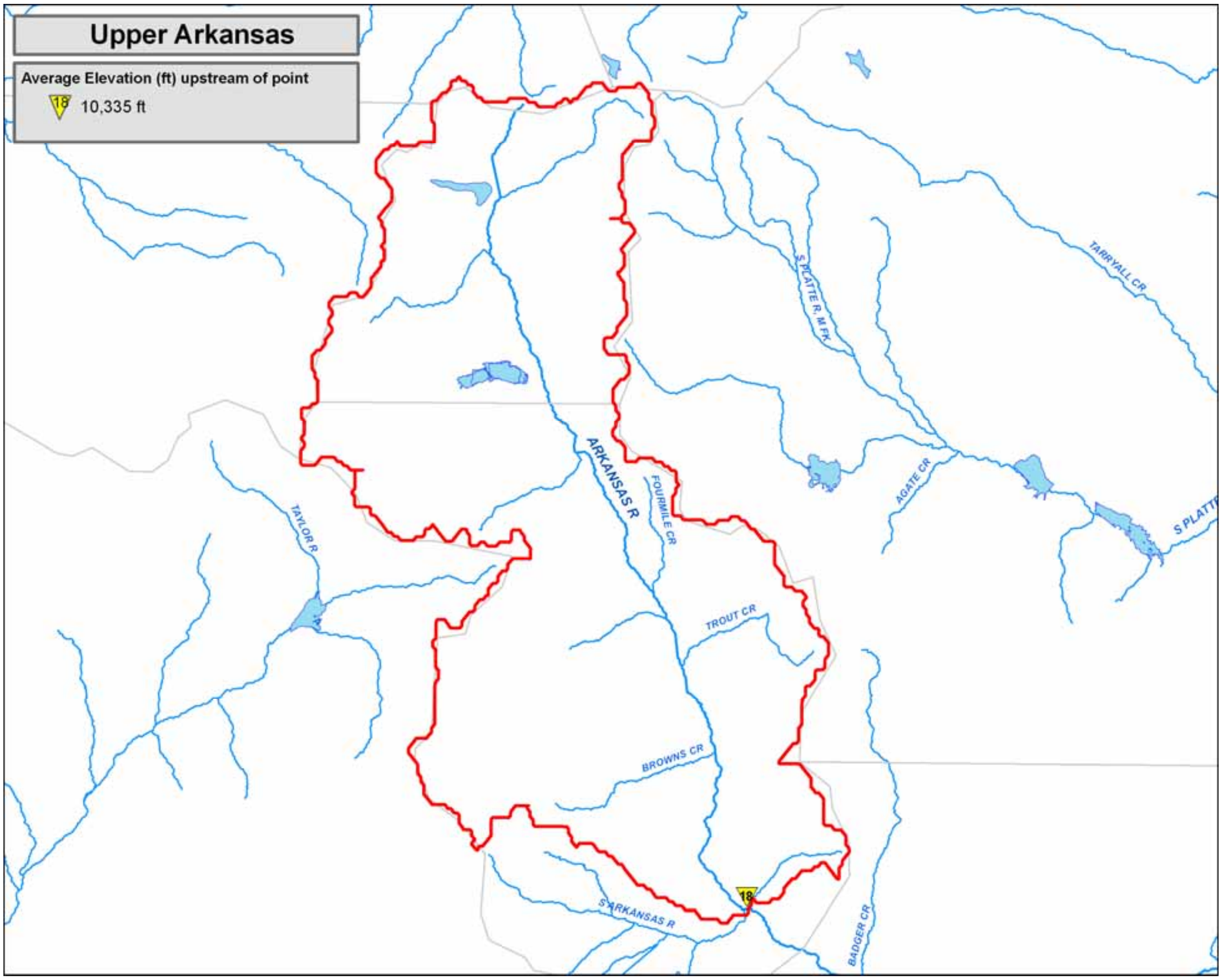


Figure 2.18 Arkansas Basin Study Point

Potential Evaporation Curve – Sacramento Model

The monthly potential evapotranspiration (PET) curve for natural vegetation is a calibration component of each sub-basin in the Sacramento model and represents the monthly variation in the maximum ET that would occur if soil moisture were unlimited. Actual ET (AET) is computed at each time step in the model as a function of PET and soil-moisture, with reduced soil moisture corresponding to reduced AET. The PET curve, along with other calibration parameters and model states such as the capacity of soil zones for holding water, the percentage of forest cover, and the amount of ground covered by snow are key parameters of model simulated ET. Temperature is not explicitly considered in the ET computation in the Sacramento model as changes in ET caused by increased temperature are represented as adjustments to the calibrated PET curve. The PET curve is, however, related to prevailing temperatures and land cover in the area. As such, PET is typically estimated using temperature-driven ET estimation methods, such as Penman-Monteith.

Because each basin was developed and calibrated independently by different NWS offices, the methods used to develop PET curves were different across the basins. In the South Platte basin, the Penman-Monteith method was used to estimate the PET curve for each sub-basin, with adjustments for calibration. In the Colorado basin, a single PET curve was developed and then adjusted for elevation using factors for each sub-basin. In the Arkansas basin, a general PET time series was developed, and a scaling factor was applied to each sub-basin to take into account unique sub-basin characteristics.

By making minor adjustments to the PET curve, a modeler can calibrate the effects of natural vegetation and other unique physical characteristics of the basin that govern ET and the resulting simulated surface runoff. Curve values are typically similar in shape across watersheds, with some modification for local effects such as elevation or differences in vegetation types.

Calibration Approach

The calibration effort balanced accurate simulation of the monthly water balance with accurate representation of daily hydrograph shapes and magnitudes of flows. Where only monthly flow data were available, the approach to calibrating the models relied on matching the volume represented by the monthly accumulation of simulated daily flows. The updated simulation at Homestake Creek after calibration is shown in Figure 2.19**.** In this basin the annual bias was improved by increasing and better simulating the flow in June, which is the peak volume month. It is possible that the flow time series used in the previous calibration, which were not available for comparison, may not have accounted for all of the diversions that have been identified in the undepleted flows developed for this study, resulting in parameters that produced less runoff in the summer months. It may be noted from the figure, however, that the previous calibration matched very nearly the computed undepleted flow and that there was only minor opportunity for improvement in the updated calibration.

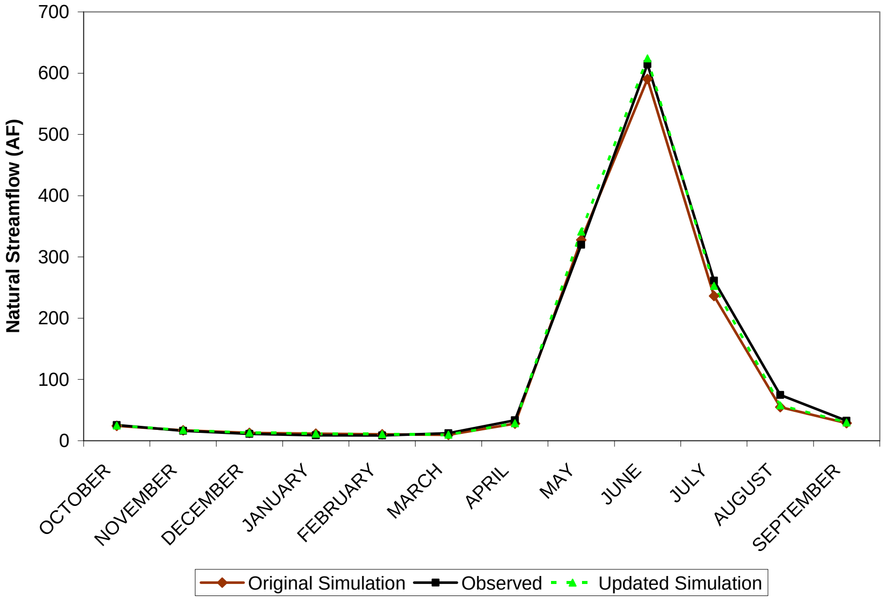


Figure 2.19 Calibration Improvement at HMSC2 (Homestake Creek at Gold Park)

WEAP Model Development

The WEAP21 Decision Support System (DSS) makes use of an internal, lumped parameter hydrologic model that simulates the hydrologic cycle, including surface and sub-surface flows, ET, and groundwater-surface water interactions. Figure 2.20 is a simplified schematic of the rainfall-runoff model in WEAP. The associated parameters used to represent the hydrologic cycle are: Fractional area, *fa*; Relative storage, *Z*; Potential ET, *PET*; Observed Precipitation, *PObs*; actual ET, *Et*; relative storage for each land use fraction, z_{fa}; irrigation threshold, T_{fa}; hydraulic conductivity, *HC and* HC_{fa}; crop coefficient, kc_{fa}; *runoff resistance factor*, rr_{fa}; partitioning fraction, *f;* and total water capacity, *Wc and* Wc_{fa} .

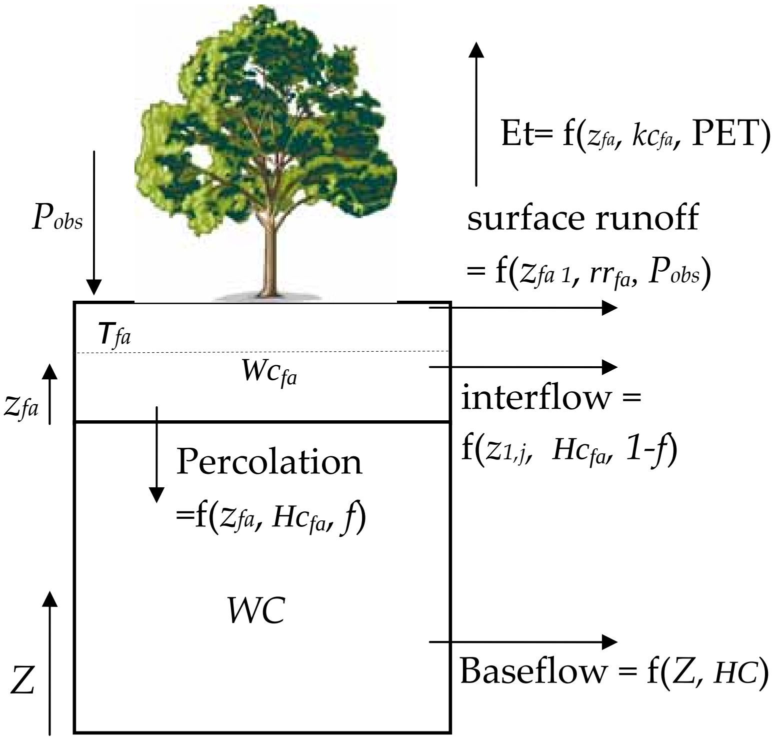


Figure 2.20 Elements of the lumped-parameter hydrologic model in WEAP

A WEAP21 model is spatially oriented, with a study area configured as a set of contiguous catchments, each assigned a unique climate forcing dataset, and in this study, adopts a weekly time step. The study area was configured as a set of contiguous catchments defined along elevation zones using GIS. The catchment can be further subdivided into an arbitrary number of fractional areas (*fa*'s) according to soil and/or land use, and can be overlaid with a network of rivers, canals, reservoirs, demand centers, and other water features, although these objects are not used in this study (Figure 2.21). The hydrologic response of each fractional area is depicted by a two-bucket water balance model that tracks relative storages, z_{fa} and *Z*, by partitioning water into ET, surface runoff, interflow, percolation, and baseflow (Figure 2.20). Each fractional area (*fa)* includes a plant/crop coefficient (kc_{fa}); a conceptual canopy density

(cd_{fa}) parameter (Kergoat 1998); water holding capacities (WC and Wc_{fa}, mm) and hydraulic conductivities (HC and Hc_{fa}, mm/time); and a partitioning fraction (f) that determines whether water moves horizontally or vertically.

An energy-temperature snowmelt algorithm, which includes liquid and solid temperature threshold parameters, Tl and Ts, is used to estimate effective precipitation (Pe) for each catchment.

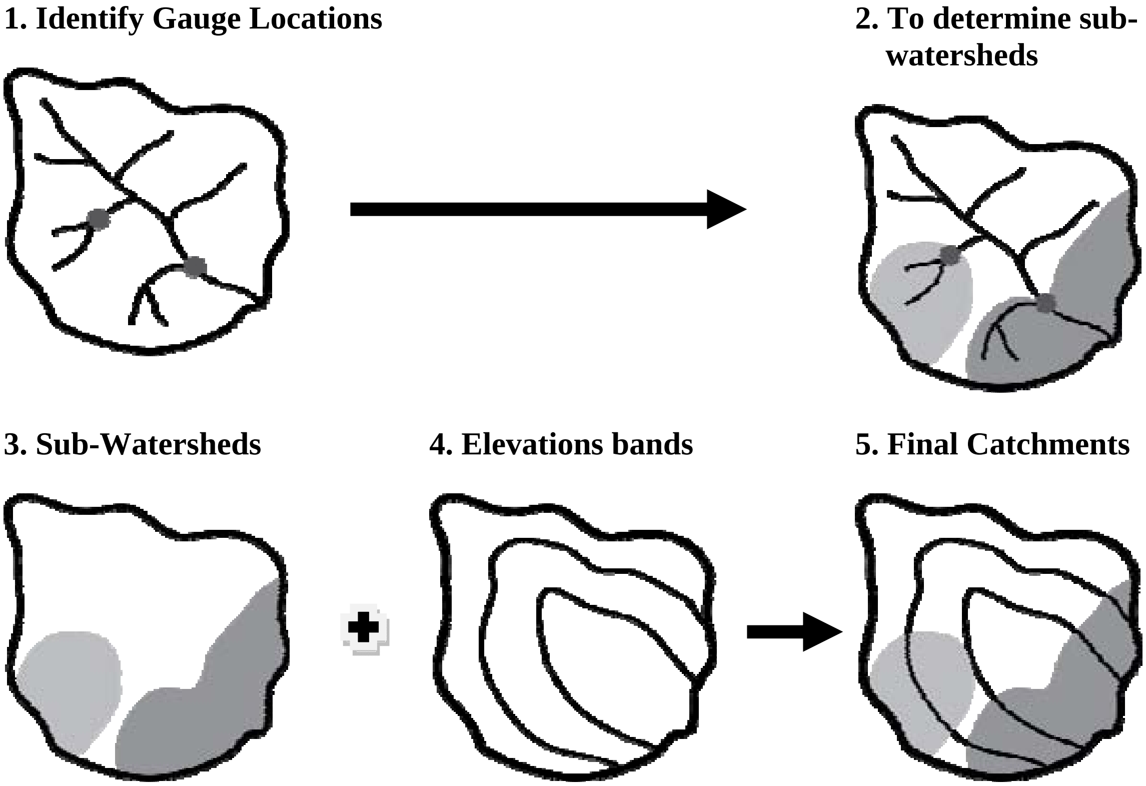


Figure 2.21 Characterization of Watersheds and banded sub-catchments

Due to the importance of snow processes in Rocky Mountain hydrology and modifications to the WEAP21 algorithm used in this effort and not presented in Yates, et al. (2005a, 2005b), the snow accumulation and melt module is described here. WEAP21 includes a simple temperature-index snowmelt model which computes an effective precipitation (P_e). The model estimates snow water equivalent and snowmelt from an accumulated snowpack in the catchment, where m_c is the melt coefficient given as,

$$m_c = \begin{cases} 0, & T_i < T_s \\ 1, & \mathrm{T_i} > T_l \\ \dfrac{T_i - T_s}{T_l - T_s}, & T_s \le T_i \le T_l \end{cases} \qquad \text{Eq. 1}$$

with T_i the observed temperature for period *i*, and T_l and T_s are melting and freezing temperature thresholds, with the melt rate given as

$$m_i = \min(Ac_i m_c, Em) \qquad \text{Eq. 2}$$

Snow accumulation, Ac_i is a function of m_c, m_i, and the observed total precipitation, P_i

$$Ac_i = Ac_{i-1} + (1 - m_c)P_i - m_i \qquad \text{Eq. 3}$$

E_m is the available melt energy converted to an equivalent water depth/time, and is a function of the net radiation and latent heat of fusion.

The calculation for net radiation considers the albedo which is modeled using a simple algorithm that decreases albedo through time to represent the "ripening" of the snow surface (USACE 1998). The model user specifies a "new" snow albedo value, A_N, and the minimum albedo of a snow-free surface, A_O. Albedo is set at the "new" value following snowfall; it is then decreased by approximately 0.05 for each simulation week until it reaches the minimum albedo value, typically set at 0.15.

WEAP Model Implementation

Four independent WEAP applications were developed, consistent with the basins identified in Table 2.5 through Table 2.8. These include 1) The Upper Colorado River Basin with aggregate flows to Cameo, 2) the Upper South Platte Basin with aggregate flows to Henderson; 3) the Arkansas River Basin with aggregated flows to Salida; and 4) the four individual basins of the Northern South Platte, including Boulder Creek, the Saint Vrain; the Big Thompson, and the Cache La Poudre River. Each model was calibrated against the same undepleted flow estimates used by the Sacramento Model for the period 1950 through 2005. In addition to the 18 gauge locations where undepleted flows were simulated, several other simulation points were included that correspond to important management locations throughout the watersheds. Most notably, this is the case in the Upper Platte Basin, where the locations of the main reservoirs on the system are identified, including Antero, Spinney, Eleven Mile, Cheesman, and Chatfield.

Each of the four WEAP basin applications used a weekly time step for the period 1950 through 2005. The climate forcing data included precipitation, temperature, and relative humidity, which are provided on a 12-km grid from the daily dataset of Maurer et al. (2002). This gridded dataset is based on station data across the country, where a topographic adjustment is used to create the regularly spaced, climate forcing dataset for the contiguous US. Individual watersheds are a collection of sub-watersheds that are principally defined by elevation band and land use, with a single climate forcing defined for each sub-watershed from the Maurer gridded dataset. Average net radiation is computed internally based on latitude, day-length, and surface albedo, which is used to estimate PET and snowmelt.

A GIS process was used to compute the total area of each banded sub-catchment and the fractional land cover it contained according to eight land cover classes that include: agriculture, barren, forest, rangeland, tundra, urban, water, wetlands. The latitude-longitude centroid of each sub-catchment was approximated by visual inspection, and then used to retrieve the daily climate record from the Maurer dataset (Maurer et al. 2002). For each of the banded catchments, a climate forcing dataset was constructed from a single 1/8th degree Maurer grid point. A weekly average of temperature and humidity, and total precipitation were then computed for each banded sub-catchment and entered into WEAP. The resulting disaggregation of the watersheds resulted in more than 150 individual catchment objects. Since climate data are needed through 2005 and the Maurer dataset ends in 2000, a simple scaling procedure was used to generate weekly time series from 2001 through 2005. For each banded catchment, a weekly mean climate forcing dataset was multiplied by an annual scaling factor to shift mean precipitation either upward or downward to reflect wet or dry years. In this way, the severe drought of 2002 was represented. Only precipitation was scaled, as the other climate variables (temperature, windspeed, and humidity) simply repeated the weekly average values of the historical period for the years 2001 through 2005.

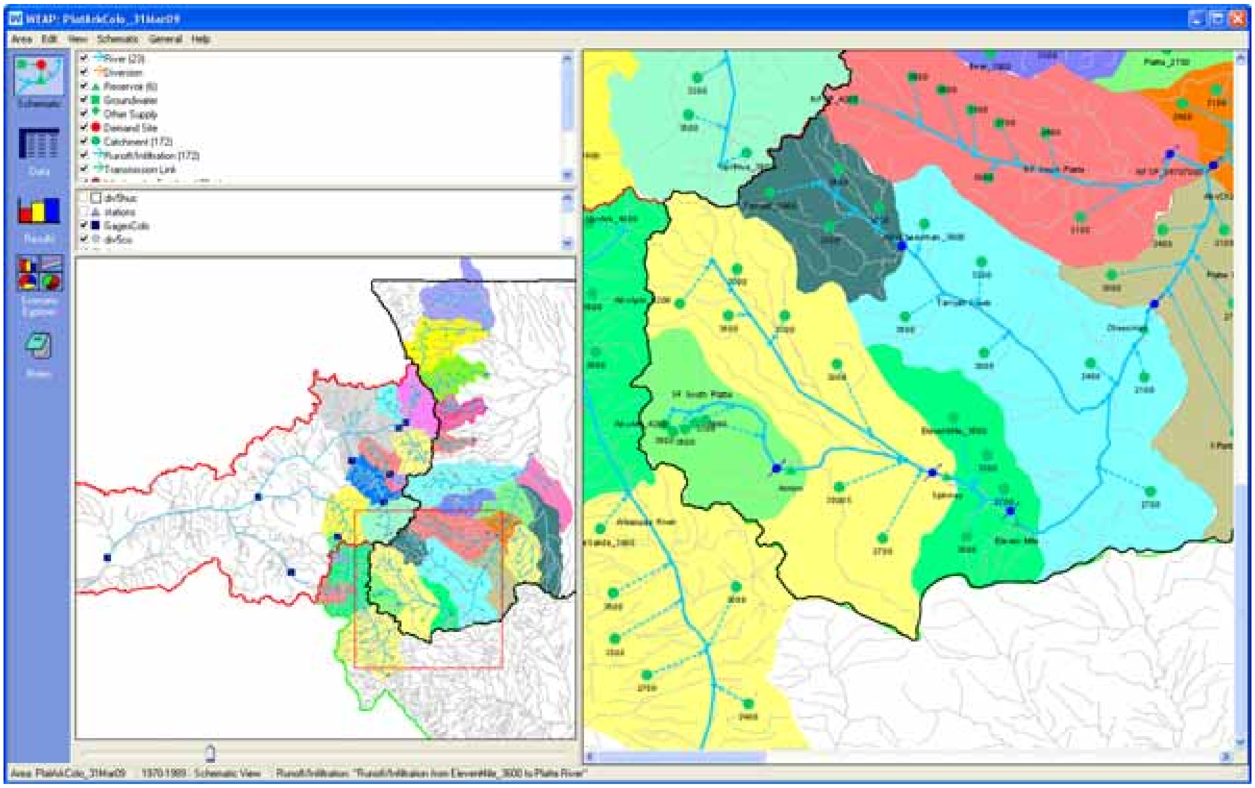
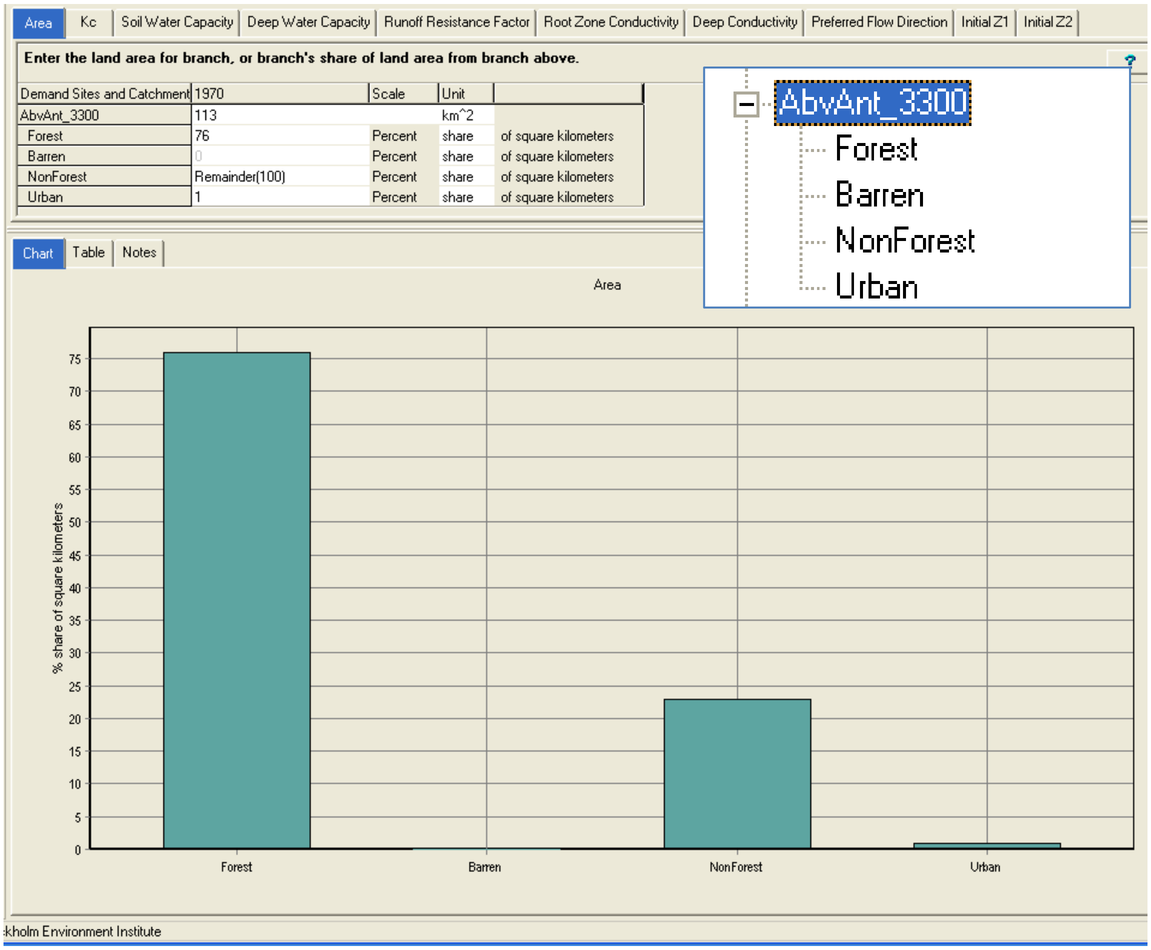


Figure 2.22 The WEAP application of the Platte, Arkansas, and Upper Colorado River Basin, with area enlarged over the Upper South Platte Basins

Figure 2.22 shows the combined WEAP application for the Platte Basin, where the catchment (that is the South Fork of the South Platte above Antero Reservoir) consists of 5 sub-catchments defined along the 2400 to 4200-meter elevation bands and are referred to as AbvAnt_2400, AbvAnt_2700, and AbvAnt_4200. Using the land cover dataset, each sub-catchment was characterized with four possible land uses including Barren, Forested, Non-Forested and Urban. As an example, the AbvAnt_3300 sub-catchment is 113 km^2 in size, and is 76% forest, 23% non-forest, and 1% urban, as shown in Figure 2.23. This number of land use categories is arbitrary, and based on user choice.



Enter the land area for branch, or branch's share of land area from branch above.

Demand Sites and Catchment	1970	Scale	Unit	
AbvAnt_3300	113		km^2	
Forest	76	Percent	share	of square kilometers
Barren	0	Percent	share	of square kilometers
NonForest	Remainder(100)	Percent	share	of square kilometers
Urban	1	Percent	share	of square kilometers

Figure 2.23 Land use specification for the AbvAnt_3300 sub-catchment

The elevation banding procedure resulted in 209 unique sub-catchments that comprise the primary basins of the South Platte, Arkansas, and Colorado Rivers. These three primary basins are composed of 36 unique sub-watersheds each with a number of banded catchments, which contribute to the flow estimates at the 18 gauge locations of interest (Table 2.10). In summary, the watershed delineation procedure for the WEAP model included the identification of sub-catchments according to elevation band and land use, with a unique climate forcing dataset identified for each. Each sub-catchment was assigned a set of hydrologic parameters used by WEAP to simulate snow accumulation and melt process, track soil moisture, and simulate runoff processes.

Table 2.10 Watershed name and model information

Watershed Calibrations	CODE	Sub-watersheds	banded-catchments	Area (1000's acres)
South Platte at South Platte	PLT	7	37	
South Platte at Henderson*	HND	14	75	2964
Boulder Creek at Orodell*	BLD	1	7	58
St. Vrain at Canyon Mount*	VRA	1	8	126
Big Thompson at Canyon Mouth*	BGT	1	7	152
Cache La Poudre at Canyon Mouth*	CLP	2	12	669
Upper Colorado at Granby	UCG	1	5	
Fraser River at Granby	FRG	1	5	
Williams Fork Nr. Leal	WFL	1	4	
Blue River at Dillon	BLU	1	4	
Blue River at Green Mountain	BGR	2	5	
Homestake at Gold Park	HMS	1	4	
Roaring Fork nr Aspen	ROF	1	7	
Colorado at Cameo*	COC	13	81	4668
Arkansas at Salida*	ARK	4	19	743
Total sub-watersheds and catchments		36	209	9386

*Total upstream area is computed only for these watersheds

Model Calibration

The WEAP model was calibrated against historical, undepleted flows at the 18 gauges, primarily using the trial-and-error approach. The calibration criteria included the ability of the model to conserve total annual volume, match the weekly timing and distribution, and preserve the low-flow conditions from late summer through mid-winter. The key model parameters adjusted during the calibration process included those associated with snow accumulation and melt, such as liquid and freezing temperature thresholds, and the magnitude of net radiation during melt reflected through the albedo decay parameter. Other adjusted parameters include hydraulic conductivity, soil-water capacity, and surface runoff resistance. Initial values were estimated for all land use categories based on a broad understanding of hydrologic response. Because the hydrology model in WEAP is conceptual and can be applied across varying time steps, there are no predefined values for model parameters like soil-water holding capacity or water conductivity. Rather, those values vary with the length of the time step, such that parameters for a daily time-step model represent rapid hydrologic responses, while a weekly or monthly formulation with the WEAP model will represent longer-term hydrologic responses.

An initial set of soil-related hydrologic parameters was developed that could be applied across all the watersheds and captured the seasonal and inter-annual variability of flow measurements across all catchments. These parameters included soil-water holding capacity (mm), hydraulic conductivity (mm/week), and a unitless surface runoff resistance factor (*Rrf*)

The most sensitive model parameters were then adjusted on a watershed-by-watershed basis, including soil-water capacity, hydraulic conductivity, melt and freeze temperatures, additional radiation factor, and preferred flow direction to account for fine-scale differences in watershed characteristics not captured by the aggregated parameters. Table 2.11 summarizes both the uniformly applied and basin varying parameters used in all four WEAP applications.

Table 2.11 The range of the calibration parameters

Model Parameter	Value
Crop Coefficient*, *kc*	1.1 (Forest; Urban); 1.2 (non-Forest; barren)
Runoff resistance factor*, *Rrf*	Barren = 3, Non-Forest = 8, Forest = 12, Urban = 1
Albedo, new snow*, A_N	0.80
Albedo, old snow*, A_O	0.15
Soil Water Capacity, Wc_{fa}	125 to 320 mm
Hydraulic Conductivity, Hc_{fa}	20 to 100 mm/week
Runoff Resistance, rr_{fa}	1.0 to 6.0
Temperature Thresholds, T_s *and* T_l	-5°C to +6°C

*These parameters were applied uniformly across all watersheds

Climate Forcing Datasets for each Model

Both the WEAP model and the Sacramento model simulate historical streamflow sequences based on historical temperature and precipitation inputs. These inputs are known as climate forcings for the models. As noted previously, the independent climate forcing datasets were developed for each model based on their historical applications and unique model characteristics and needs. Although the simulation process is similar, the temperature and precipitation data are from different sources.

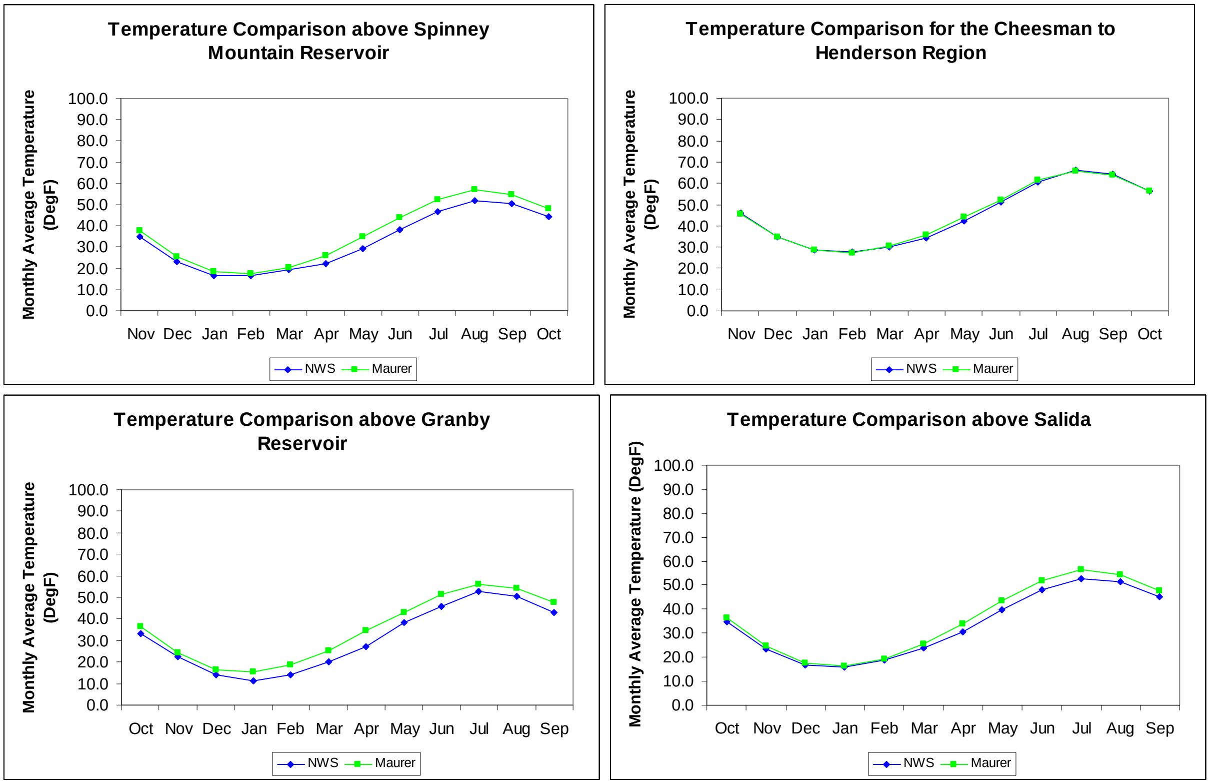
For the Sacramento model, the NWS prepared historical time series of Mean Areal Precipitation (MAP) and Mean Areal Temperature (MAT) data for each sub-basin and for specific elevation zones within sub-basins that exhibit significant elevation changes. These time series were based on individual weighting schemes for gauges in and near each basin or elevation zone. All the temperature and precipitation data were compared between nearby gauges to identify and fix poor input data. The process is typically automated with some help from database tools, comparing for error conditions such as minimum daily temperature greater than maximum daily temperature (Tmin > Tmax), stations with temperatures that are significantly different than surrounding station temperatures, and excessively large local precipitation events. In the case of the Maurer et al. (2002) dataset used by the WEAP model, the process was similar, although it is important to note that this is a national dataset, with no location specific corrections.

A comparison of these datasets was performed to determine whether either dataset showed a major bias that could introduce large streamflow simulation differences between the models. To some extent, the calibration process compensates for bias in the datasets as model parameters are adjusted to more accurately simulate observed streamflow response. Modeled sub-basin boundaries are similar for both models, defined by major geographical features and gauge locations. Direct climate data comparisons could only be performed by summarizing data for areas above the gauge locations used in this study. The selected comparison regions are outlined in Table 2.12.

Table 2.12 Forcing Data Comparison Regions

Basin	Region
South Platte	Spinney Mountain Reservoir and above
	Cheesman to Henderson
Upper Colorado	Lake Granby and above
	Dillon and above
	Dotsero to Cameo
Arkansas	Salida and above

For each region, the climate forcing data was compared for both temperature and precipitation. In all cases, the precipitation data compared well with the Maurer et al. dataset tending to be slightly wet and having warmer summers. These small differences suggest that the two different climate forcing datasets will not lead to large differences between the SAC-SMA and WEAP-simulated streamflows. In Figure 2.24, the area-weighted average monthly temperature pattern for the basins above the Colorado near Granby are shown for each model. The Maurer dataset shows higher average temperature values for each month of the year. Figure 2.25 compares the monthly precipitation between the model forcing datasets at the same location. The monthly trend, as well as average annual values, are consistent, although specific months can show larger differences. Similar results were found for the other basins evaluated, with consistently high correlation between monthly values for each model.



Temperature Comparison above Spinney Mountain Reservoir

Temperature Comparison for the Cheesman to Henderson Region

Temperature Comparison above Granby Reservoir

Temperature Comparison above Salida

Figure 2.24 Monthly temperature comparison between, the NWS and Maurer datasets for the South Platte above Spinney, the South Platte between Cheesman and Henderson, the Colorado including Granby Reservoir, and the Arkansas above Salida

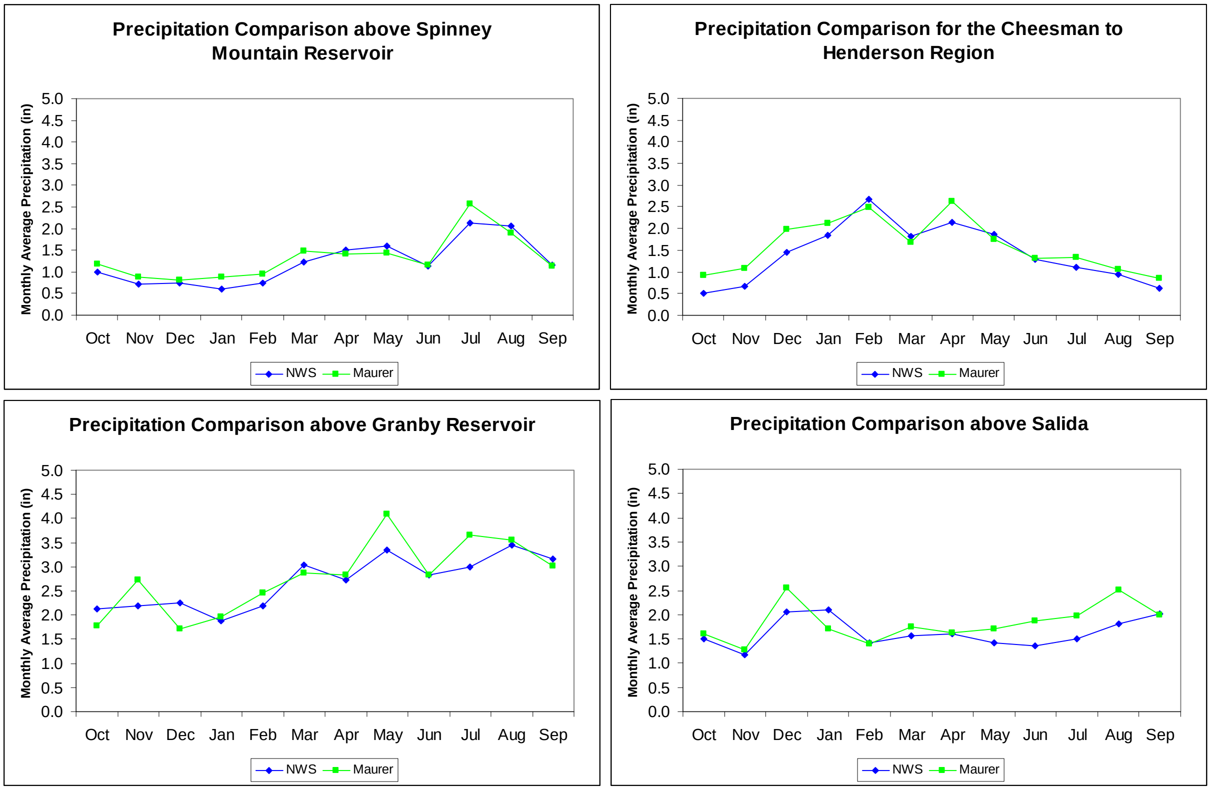


Figure 2.25 Monthly precipitation comparison between, the NWS and Maurer et al. datasets for the South Platte above Spinney, the South Platte between Cheesman and Henderson, the Colorado including Granby Reservoir, and the Arkansas above Salida

Input Data Extension for SAC/SMA in the Arkansas

The original MAP and MAT data for the Sacramento model in Arkansas basin ended in water year 1999. Because of the importance of the post-year-2000 drought period, the climate forcing dataset was extended as part of this study using a similar methodology to that used by the NWS in developing the original dataset. Temperature and precipitation gauge data were obtained and quality controlled for the Arkansas basin. Data anomalies were compared and outliers that were inconsistent with data from surrounding stations were removed from the dataset by setting the values to missing. The resulting quality-controlled station data were applied to each sub-basin using station weights to calculate the average temperature and precipitation across the entire basin. This procedure resulted in MAP and MAT datasets for the Arkansas basin extending from January 1951 through the end of water year 2005.

Input Data Extension for the 1950-2005 Water Years

Several periods of missing data remained in the climate dataset for each model, as shown in Figure 2.26. The Maurer dataset does not extend beyond 1999. The NWS datasets for the Colorado and the Arkansas do not begin until calendar year 1951. The NWS dataset for the South Platte ends after September, 2004.

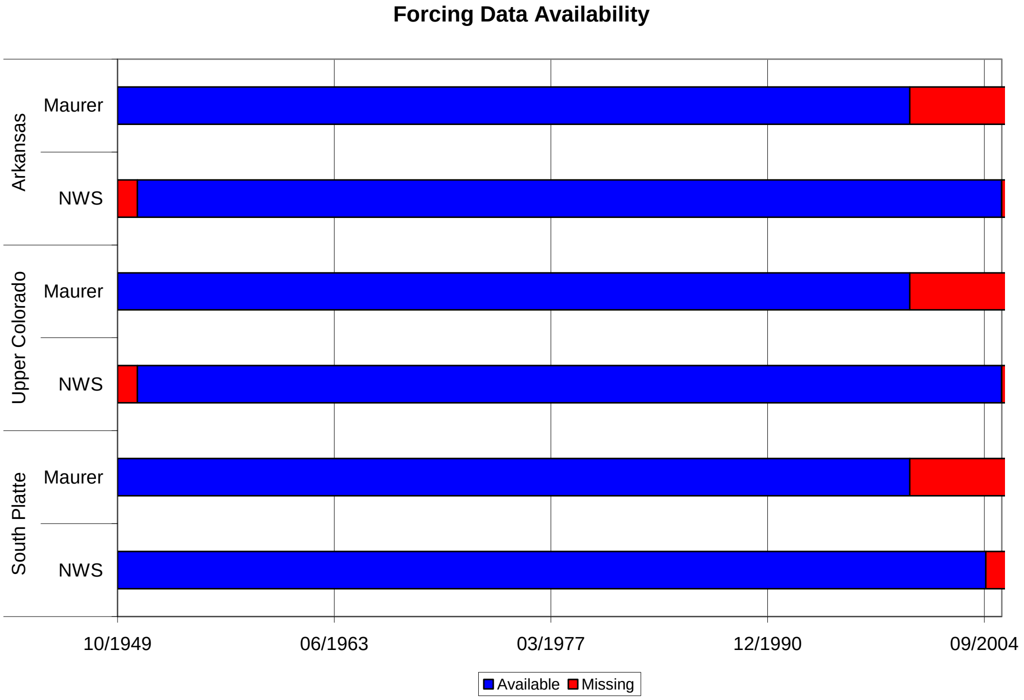


Figure 2.26 Forcing Data Availability by Basin and Source

It was important to the participants that the forcing datasets include the complete period of interest to enable comparisons for a consistent period and to have complete simulated datasets of climate-adjusted streamflow. In the absence of available historical data, climate forcing data from years with similar hydrologic response to the years with missing climate data were chosen to fill the missing periods. Historical undepleted flow at key gauge locations was used to determine the best replacement year for the missing data. For each missing year, the five years with similar annual undepleted streamflow were selected for comparison. Of those five years, the year with the best fit (based on the Nash-Sutcliffe Efficiency statistic for monthly flow) was selected as the replacement year for the missing data. All input data from the source year were used as a proxy for the missing data. Use of this data in subsequent analysis has the effect of repeating a historical year that produces a similar monthly and annual correlation of undepleted flow to the missing year.

Comparison of Simulated Streamflow for Each Model

For each model, the calibration statistics were compared on a monthly basis to the calculated historical undepleted streamflow. These statistics provide measures of goodness of fit, while highlighting different aspects of the fit. Several statistical measures were used to evaluate the skill of each hydrologic model and its ability to simulate the historical streamflow for each of the gauge locations. These included the correlation coefficient, the root mean square error (RMSE) and the Nash Sutcliffe Efficiency (NSE). $Q_{s,i}$ and $Q_{o,i}$ are simulated and observed streamflow for each time step i, while n is the total number of time steps for the simulation period.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Q_{s,i} - Q_{o,i})^2}{n}},$$

The RMSE is a quadratic scoring rule that measures the average magnitude of the error, with the difference between simulated and corresponding observed values each squared and then averaged over the sample. Finally, the square root of the average is taken. Because the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. This means the RMSE is most useful when large errors are particularly undesirable. The RMSE can range from 0 to ∞, and is a negatively oriented score meaning lower values are better. The NSE metric is given as

$$E_f = 1 - \frac{\sum_{i=1}^{n} (Q_{s,i} - Q_{o,i})^2}{\sum_{i=1}^{n} (Q_{o,i} - \overline{Q_o})^2}.$$

where $\overline{Q_o}$ is the simulated average and other terms are defined above. This NSE is a measure of a model's ability to simulate flow, as opposed to just using the average value of the measured data. Typically, an acceptable value should be greater than 0.5 while a good value should be greater than 0.7. A value of 0.0 means that the model performs no better than a simple average of the observed time series. Other statistics compared include the mean annual flow volume, the mean annual volume bias, and the standard deviation of the monthly volume, with tables of computed statistics for the eighteen calibration points provided in Appendix A.

To determine the effectiveness of each model in simulating a broad range of climatological conditions, calibration statistics were computed separately for wet, dry, and normal years, defined as follows: for the 56-year period, the years with the highest 25% of flows were classified as wet, those with the lowest 25% of the years were classified as dry, and the those with the remaining 50% were classified as normal. The classification of wet and dry years was performed separately for each gage location. The statistics presented in Appendix A include these breakdowns. Graphical representations of the model performance on an average monthly basis are provided in Figure 2.27 through Figure 2.32, below, at six selected calibration points: the Blue River below Dillon; the Colorado at Cameo; the South Platte above Spinney Mountain Reservoir; South Platte at South Platte; the Cache la Poudre at Mouth of Canyon; and the Arkansas at Salida. Each figure compares model simulations against historical undepleted flow for the three categories (wet years, normal years and dry years). Note that the range of the y-axis in each of these figures is different to help emphasize model differences.

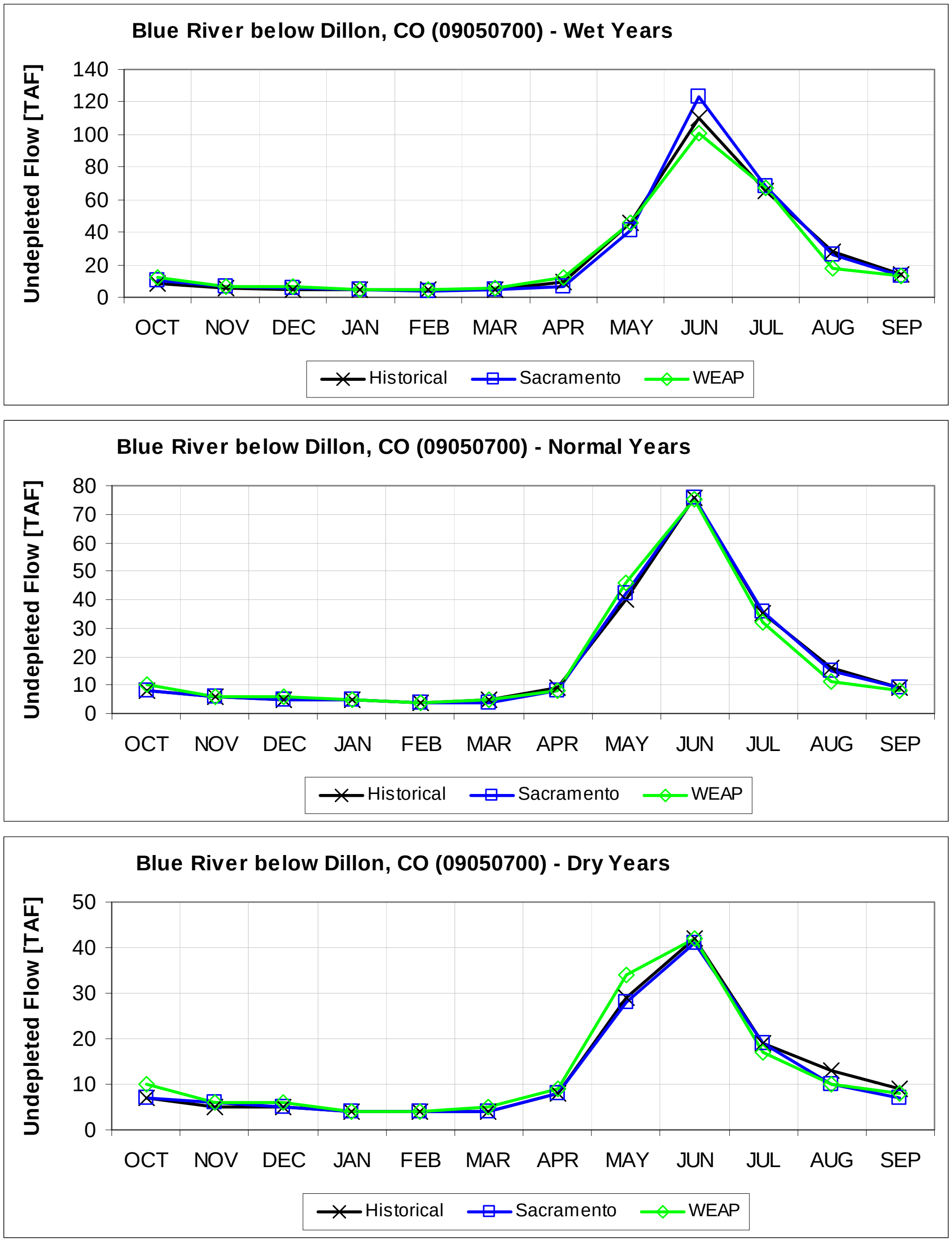


Figure 2.27 Calibration Comparison for the Blue River below Dillon (Monthly Average)

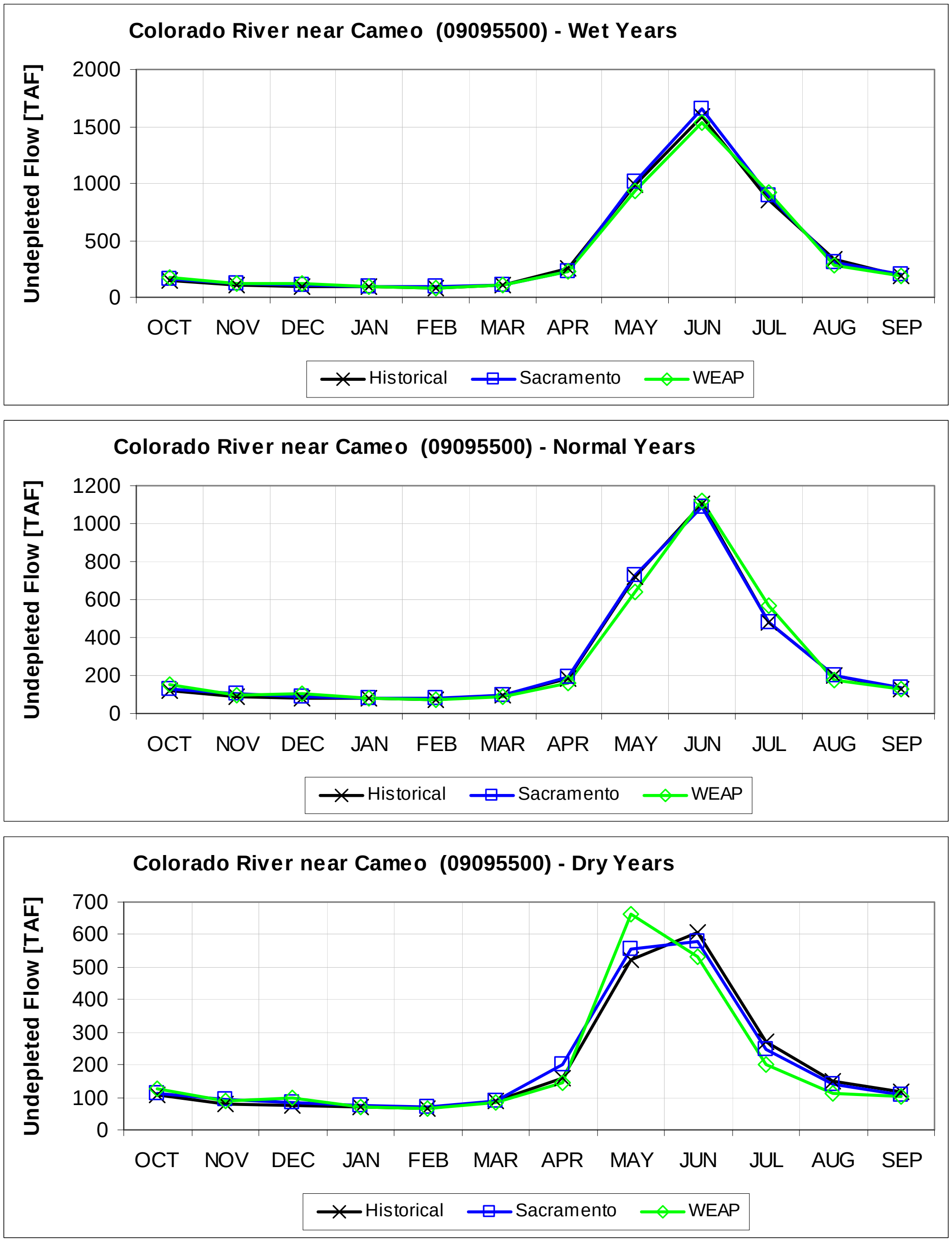


Figure 2.28 Calibration Comparison for the Colorado River at Cameo (Monthly Average)

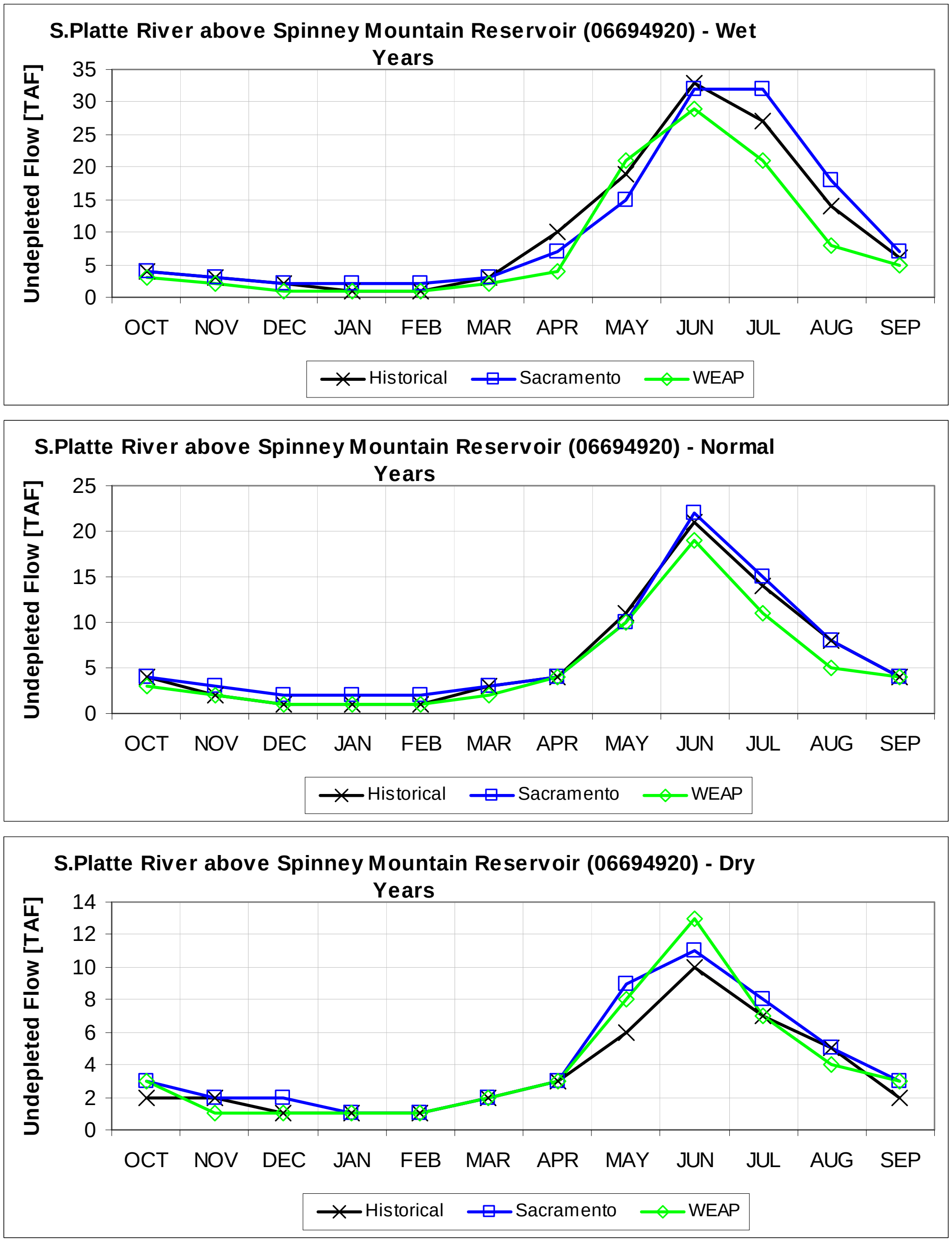


Figure 2.29 Calibration Comparison for the South Platte above Spinney Mountain Reservoir (Monthly Average)

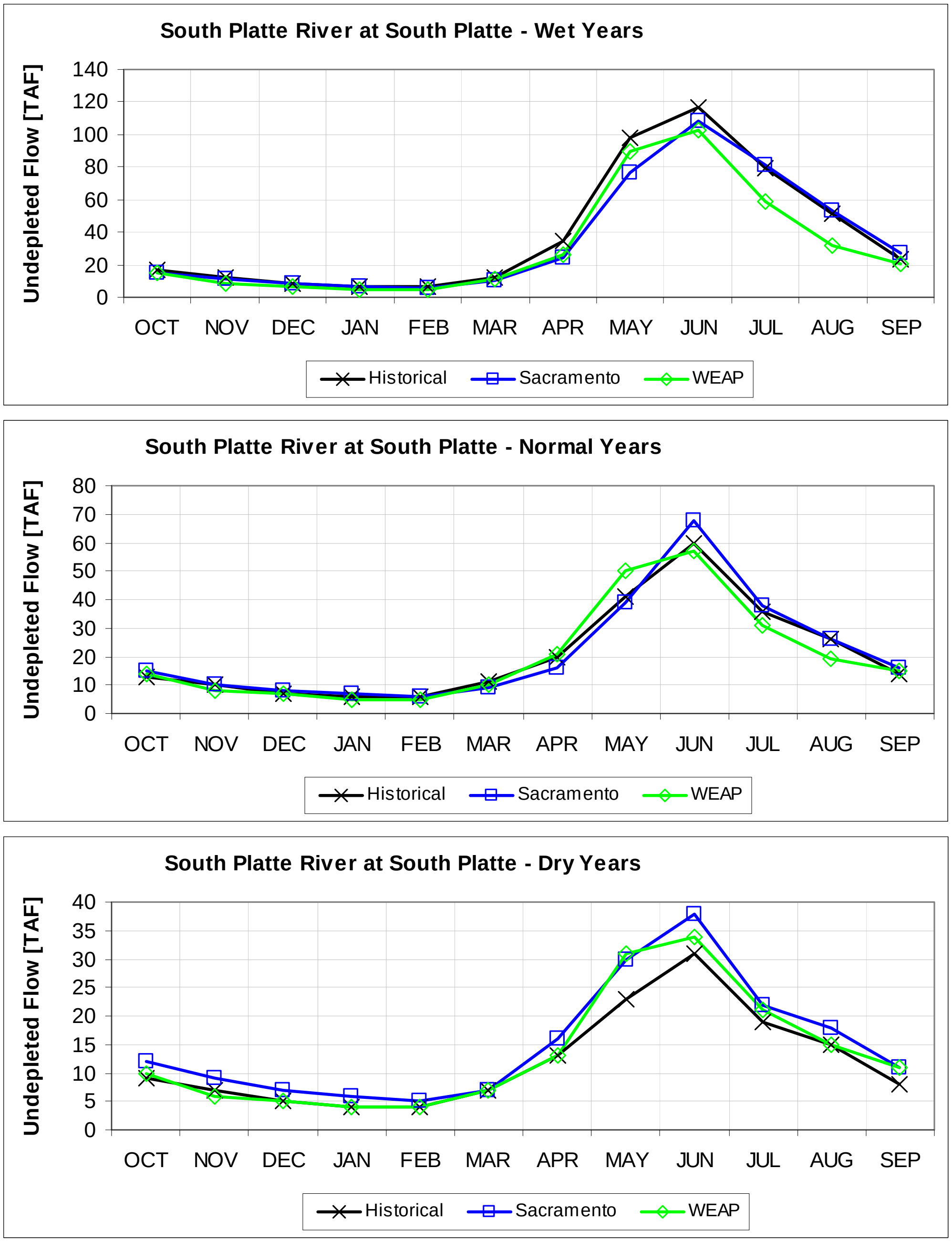


Figure 2.30 Calibration Comparison for the South Platte at South Platte (Monthly Average)

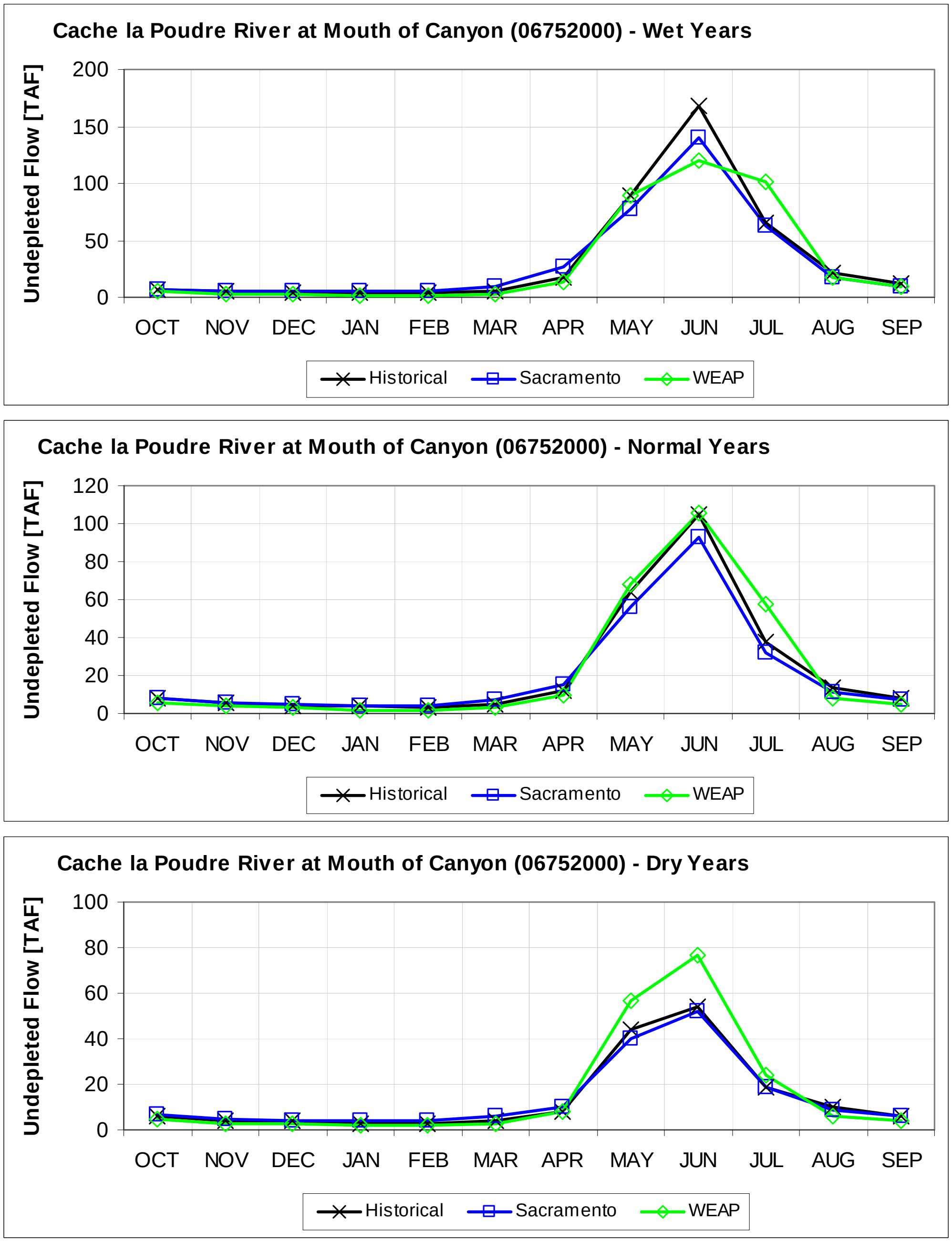


Figure 2.31 Calibration Comparison for the Cache la Poudre at Mouth of Canyon (Monthly Average)

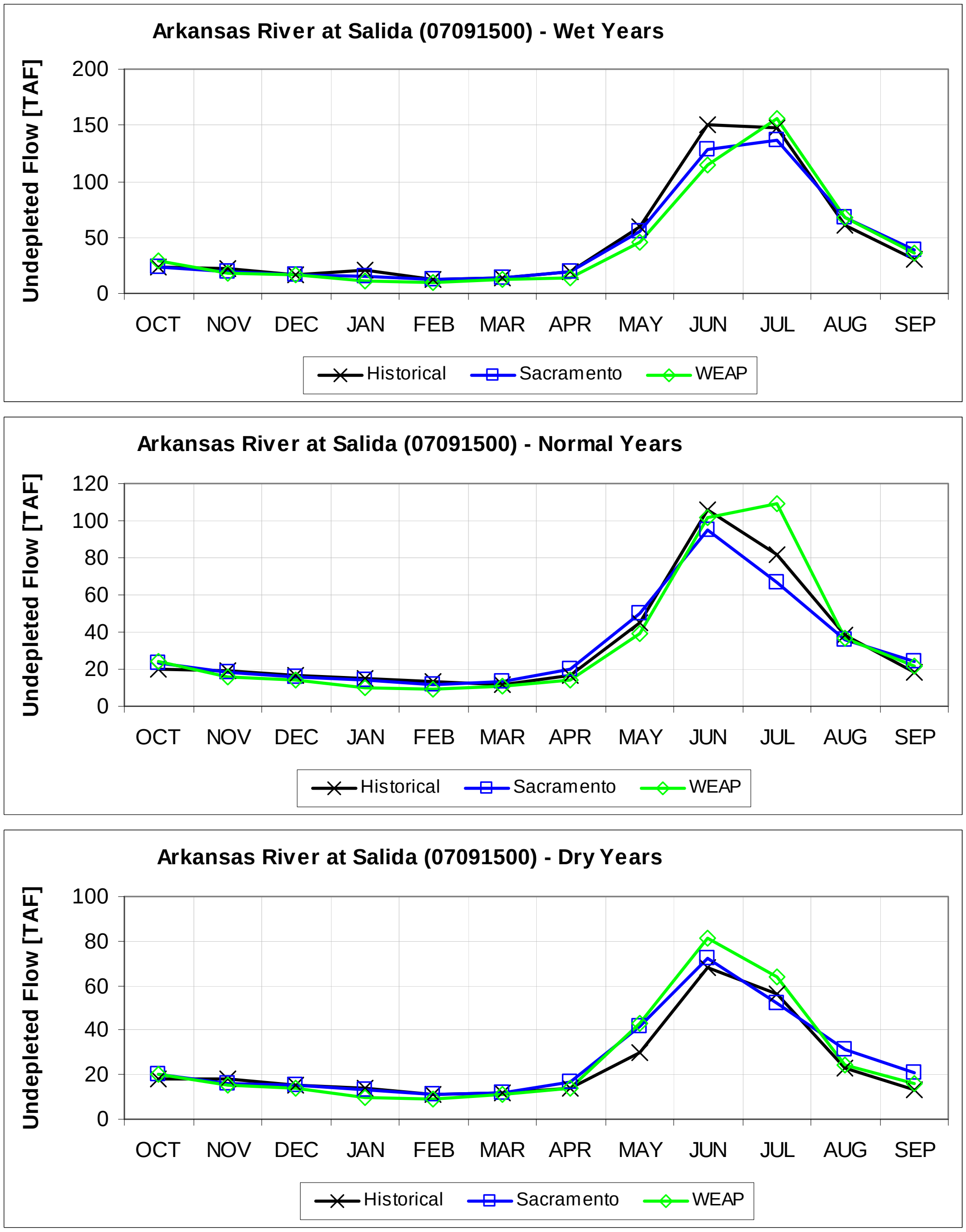


Figure 2.32 Calibration Comparison for the Arkansas at Salida (Monthly Average)

Both the Sacramento and the WEAP model show similar skill in reproducing the monthly mean pattern of runoff in wet, normal, and dry years. In some cases, the Sacramento model and WEAP models produce different runoff patterns and timing (e.g. Sacramento is greater in mean June runoff in wet years; WEAP's peak runoff in dry years is earlier than observed and Sacramento simulated; WEAP tended to have less runoff and Sacramento more runoff in late spring in the South Platte in wet years). For the Poudre and Arkansas Basins, WEAP showed greater July streamflow. In general, WEAP tends to produce more spring runoff in dry years, while the Sacramento model's calibration statistics (e.g. the NSE values of the Sacramento model given in Appendix A) tended to be higher than WEAP's NSE values, suggesting better calibration in many cases.

TASK 4: ASSESSMENT OF STREAMFLOW SENSITIVITY TO CLIMATE CHANGE

The analysis of streamflow sensitivity to climate change was performed in two stages. In the first stage, a simple sensitivity analysis was used to test and demonstrate the hydrologic simulation approach and also to test the sensitivity of each model at each gauge location to a uniform temperature increase (with no change to precipitation) and to a uniform precipitation adjustment (with no change to temperature).

The second stage was to perform a GCM-based sensitivity analysis to assess model response to possible climate change represented by specific projections in which the temperature and precipitation adjustments vary spatially over the study area and temporally from month to month.

The Response of Potential Evapotranspiration to Temperature Change

An important component of the hydrologic simulation requiring special treatment in the Sacramento model is the response of Potential Evapotranspiration (PET) to temperature change. The way in which this response was represented in the first stage of the assessment was also applied in the second stage, and is therefore applicable to both stages. As noted previously, the PET is an estimate of the upper limit on moisture that the natural vegetation may remove from the surface water and the soil column through ET. Because the procedure for estimating ET demand parameters incorporates prevailing temperature, a general procedure for adjusting the ET demand parameters in response to a given change in prevailing temperature was applied using shifted minimum and maximum characteristic temperatures applied at each basin temperature gauge. Changes in estimated PET in response to changes in projected temperature were modeled as follows:

1. For each sub-basin, average baseline monthly PET was estimated using the Penman-Monteith method and temperature characteristics for each contributing temperature gauge for the calibration period.
2. For each sub-basin, a climate-adjusted monthly PET was estimated using the Penman-Monteith method and applying the modeled climate change temperature shifts to the temperature characteristics for each contributing temperature gauge.
3. The adjustment to PET predicted by the change to PET computed in step 2 was identified, generating monthly percent changes between the baseline and climate-adjusted PET values.
4. The PET adjustment factors were applied to the calibrated PET curve, arriving at a calibrated, climate-adjusted PET curve specific to the given change in prevailing temperature.

The ET demand adjustment procedure was automated as a part of the model run process, tying individual gauges to their characteristic monthly average T_{min} and T_{max} values used in the Penman Monteith equation. Additional information, such as gauge station latitude and weighting factors used by the NWS for station weights, was used to estimate the effects of each station on the overall PET curve. Figure 2.33 illustrates the average increase in PET for the basins in the Colorado River above Cameo resulting from increased temperatures for a given climate scenario. The change in simulated AET is also shown. AET is always less than PET because as the soil dries by the action of ET, there is less water available subsequently to satisfy the full potential until additional precipitation occurs. It can be seen from the figure that the ratio of AET to PET is greater in the wet spring months and smaller in the dry summer months. The figure also illustrates that although the potential may have increased in every month due to increased temperatures, the simulated actual ET is only higher in the winter and spring months when the soil moisture is sufficient to meet a portion of the additional demand, and that in the summer months the reduced availability of water in this scenario results in lower ET.

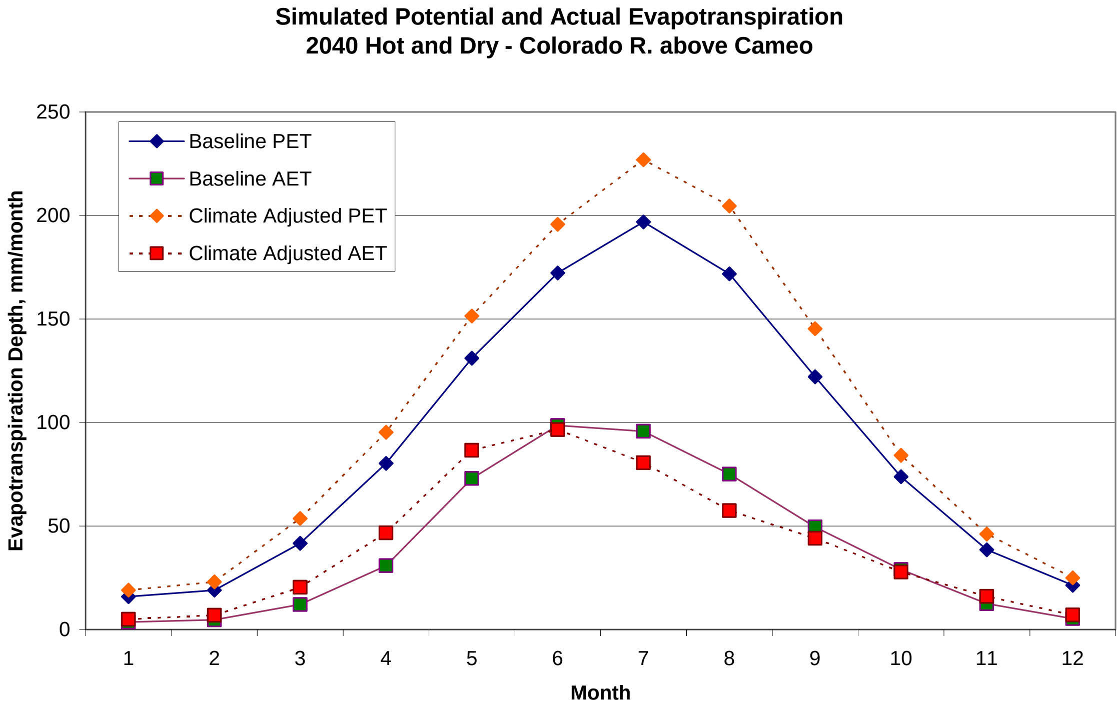


Figure 2.33 Climate Change Adjustments to the Sacramento Model PET Curve

In the WEAP model, the Penman-Monteith equation is embedded directly in the ET computation method and uses the temperature input to the model, instead of using calibrated monthly values. No additional procedure was needed to adjust the model to account for temperature-based changes to PET. It should be noted that the Penman-Monteith reference ET equation is only an estimate of the ET demand, and it does not take into account second-order effects, such as the reduction in natural vegetation in response to prolonged drought or changes in other climate variables such as relative humidity, wind speed, and solar radiation.

Simple Sensitivity Analysis (Stage 1)

The simple sensitivity assessment examined model sensitivity to simple deviations in temperature and precipitation to understand each model's sensitivity to a simple climate perturbation, to ensure that model results were reasonable and consistent with expectations, and to gain insight into model response to climate-change inputs without the complexities of temporal and spatial variability in the climate-change signal that is characteristic of GCM based sensitivity analysis.

The study team and participant representatives decided on four independent climate perturbations to test model sensitivity to a simple, uniform change in climate including two temperature and two precipitation change scenarios. The changes were chosen to reflect much of the range in the projected changes expected through 2099 (IPCC AR4 Global "Best Estimates"). For each scenario, temperature or precipitation changes were applied uniformly across all basins at each time step.

The chosen uniform temperature increases to be applied to each model were:

- an increase of 1.8 ºF (1 ºC), and
- an increase of 7.2 ºF (4 ºC).

The chosen uniform precipitation factors to be applied to each model were:

- an increase of 7.5%, and
- a decrease of 3%.

For both the Sacramento and WEAP models, the uniform temperature change was simulated by adding the chosen temperature increase to the individual temperature time-series values for each sub-basin in the model. For the Sacramento model, the PET adjustment procedure described previously was performed using the selected temperature increase for the two temperature sensitivity simulations. The models were then run to simulate streamflow using the adjusted input time series, and in the case of the Sacramento model, the changed PET parameters. The uniform precipitation change scenarios were executed by multiplying the individual precipitation time series values for each sub-basin in the model by the change factor.

GCM-Based Streamflow Sensitivity (Stage 2)

The GCM-based streamflow sensitivity analysis required the historical climate time-series inputs to the WEAP and Sacramento models to be adjusted with the monthly climate-change signals from each GCM projection, and hydrologic model simulations to be performed to compute undepleted streamflow sequences that could be compared to a baseline simulation to determine the climate change signal in streamflow response. The temperature and precipitation offsets computed previously for each GCM projection represented an average offset for the entire study area. For purposes of applying the climate change signal of a given GCM to the hydrologic models, it was necessary to prepare a gridded representation of the climate-change signal to compute individual temperature and precipitation offsets for each sub-basin in the hydrologic models.

The gridded climate change signal was prepared separately for each selected GCM projection by computing the average monthly precipitation and temperature from the GCM for each grid point for the historical period (1950-1999) and for the future period considered and computing the difference for temperature or the percent change for precipitation (recall that the two future periods considered were the 30 years surrounding 2040 and the 30 years surrounding 2070). This resulted in twelve grids (one for each month) of temperature change "deltas" and twelve grids of precipitation adjustment factors for each GCM projection that could be used to compute individual sub-basin adjustment factors for the particular projection. The climate-change simulations involved incorporating these change signals into the hydrologic models, simulating the resulting runoff, and comparing with the baseline simulation. The procedures used in applying the change signals to the hydrologic models were specific to each model.

The Sacramento Model

The following procedures were followed for each sub-basin in the Sacramento model and for each GCM projection evaluated. The precipitation change factors for all grid points covering the sub-basin were averaged for each month and for each GCM projection. Then the historical precipitation time-series values for the sub-basin were multiplied by the monthly precipitation factors for the associated months. For example, the precipitation change factors for all grid cells covering the sub-basin above Antero Reservoir from the "January" grid from the 2040 Warm-Wet GCM projection were averaged to compute a "January" precipitation adjustment factor. This factor was then applied to all of the time-series values that fall in the month of January in the Antero precipitation time series, which extends from 1950 to 2005. Similarly, the temperature changes for all grid points covering the sub-basin were averaged for each month. The average temperature change for each month was added to the historical temperature time-series values for the sub-basin for the associated months. This portion of the procedure resulted in a set of adjusted precipitation and temperature time series for all sub-basins for input to the hydrologic models. Figure 2.34 depicts an example of the grid cells corresponding to an individual sub-basin in the hydrologic model.

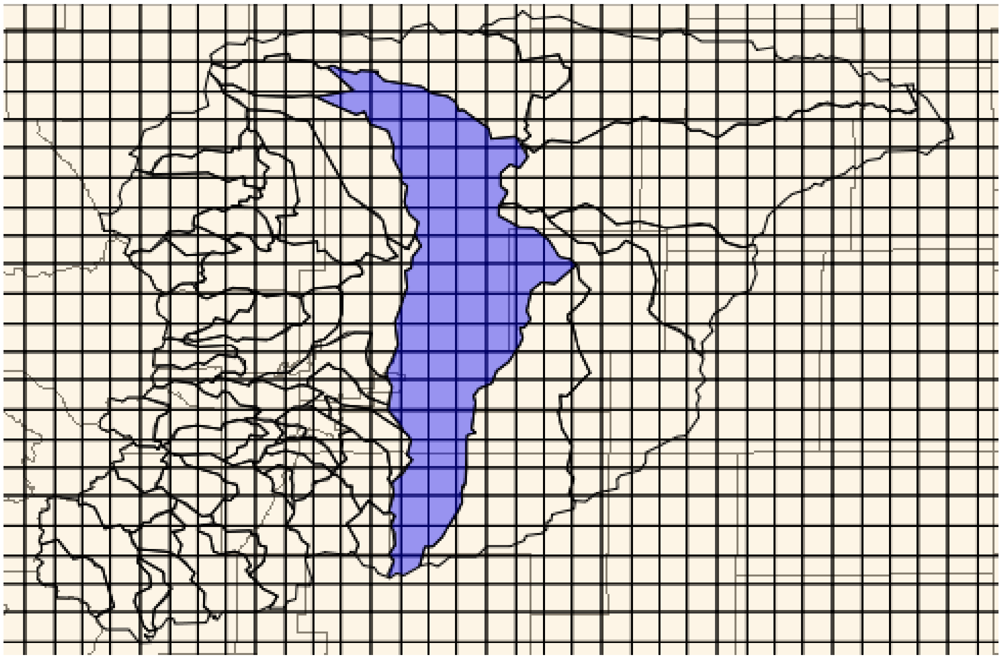


Figure 2.34 1/8th degree grid cell coverage in the South Platte sub-basins

(All grid cells with area inside the selected sub-basin are area weighted to produce a unique monthly pattern of precipitation and temperature changes for that sub-basin.)

The next step in the procedure was to modify the monthly PET parameters in the individual sub-basin hydrologic models as described previously. This procedure was identical to the procedure used for the simple sensitivity analysis, except that the temperature values used to adjust the Penman-Monteith outputs were those derived from the GCM and varied by month. Using the adjusted sub-basin model parameters and the adjusted input time series, the hydrologic simulation model was executed to compute the hydrologic response throughout the system.

The entire procedure was repeated for each of the 10 GCM projections to produce results for comparison and evaluation.

The WEAP model

The procedures followed in the WEAP model were similar to those conducted in the Sacramento model with the following differences. For each of the banded catchments, a single climate-forcing data point was selected from the 1/8th degree Maurer gridded dataset. For consistency, the same data point used for the historical climate data was then used to identify the change signal for the climate-change scenarios. The weekly, historical precipitation time-series values for each banded sub-catchment were multiplied by the monthly precipitation factors at that data point for the associated months. The average temperature change for each month was added to the weekly, historical temperature time series values for the associated months. This resulted in a set of adjusted precipitation and temperature time series for all banded sub-catchments for the WEAP hydrologic model.

Compilation of Results

A spreadsheet was prepared as a repository and display tool for the data generated by the models. The spreadsheet includes the following data, calculations, and figures:

1. Monthly time series of computed undepleted flow for each gauge location (including missing periods);
2. Filled monthly time series of undepleted flow, in which simulated flow from the Sacramento model was used to fill gaps in the undepleted flow record in item 1, above);
3. Monthly time series of simulated undepleted flow (the baseline simulation) for the Sacramento and WEAP models;
4. Monthly time series of climate adjusted undepleted flows for the four simple sensitivity simulations, the five 2040 simulations, and the five 2070 simulations for the Sacramento and WEAP models;
5. A summary sheet showing annual percent change in runoff volume between the baseline and climate change runoff simulation for each climate change scenario and gauge location;
6. A summary sheet showing annual calibration statistics for each model and gauge location;
7. A sheet permitting the selection of a single gauge for detailed analysis, with climate-change impact charts for the selected gauge, including: annual volume comparison for each climate scenario and hydrologic model; a summary annual volume organized according to year type (wet, normal, and dry); average monthly volume comparison graphs; a simulated monthly runoff plot; box and whisker plots of annual volume for the simple sensitivity runs showing max, min, mean, and standard deviation; a shift in runoff timing plot; a historical annual volume plot; and supporting tables for each plot;
8. A calibration statistics sheet for the selected gauge, including monthly summaries of historical and simulated undepleted flow, standard deviation, RMSE, NSE, and monthly

bias, and calibration graphics showing mean monthly values for historical undepleted flow and simulated undepleted flow from the Sacramento and WEAP models;

9. A climate-adjusted time-series sheet with adjustments computed by applying a time series of the ratio of undepleted-to-baseline simulated flow for each month in the historical record; and
10. A climate-adjusted time-series sheet with adjustments computed by applying average monthly ratios of baseline-to-simulated climate-adjusted flow to the historical undepleted flow time series; this sheet also includes a variety of graphics depicting the monthly percent changes.

The results spreadsheet is included with the electronic distribution of the report and as an attachment in the published version of the report. Results of both the simple streamflow sensitivity analysis and the GCM-based streamflow sensitivity analysis are presented and discussed in the *Results and Discussion* section of the report, below.

CHAPTER 3
RESULTS AND DISCUSSION

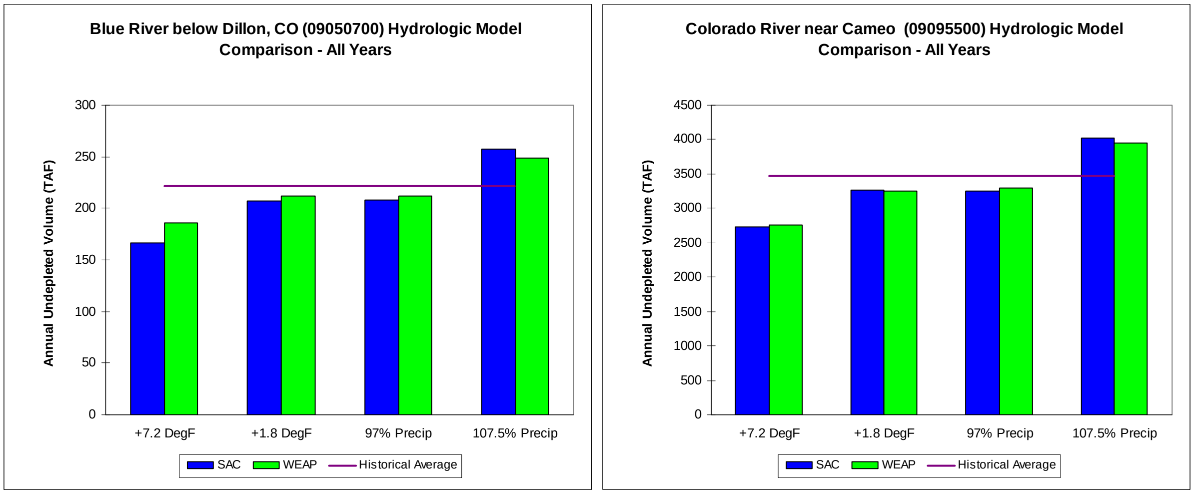
The results of the simple sensitivity analysis and the GCM-based sensitivity analysis are presented below. General results are presented first, followed by a discussion of specific findings. The results highlight the six selected gauge locations that have been noted in previous sections of the report to limit the volume of material presented. These locations are the Blue River below Dillon, the Colorado River near Cameo, the South Platte River above Spinney Mountain Reservoir, the South Platte River at South Platte, the Cache la Poudre River at Mouth of Canyon, and the Arkansas River at Salida. Tables showing the percent change in annual streamflow volume are presented in Appendix B. To remove bias inherent in the hydrologic model simulations, all results presented here are adjusted by the ratio of undepleted flow to baseline simulated flow for the respective hydrologic models.

SIMPLE SENSITIVITY RESULTS (STAGE 1)

Figure 3.1 through Figure 3.3 present for each model the average annual undepleted streamflow at six locations for each of the sensitivity simulations in addition to the historical undepleted volume. Note that the scale of the y-axis is unique for each station to emphasize the relative differences between scenarios. In summary, the temperature or precipitation changes for these scenarios were applied uniformly across all basins at each time step and included:

- A temperature increase of 1.8 ºF (1 ºC),
- A temperature increase of 7.2 ºF (4 ºC),
- A precipitation increase of 7.5%, and
- A precipitation decrease of 3%.

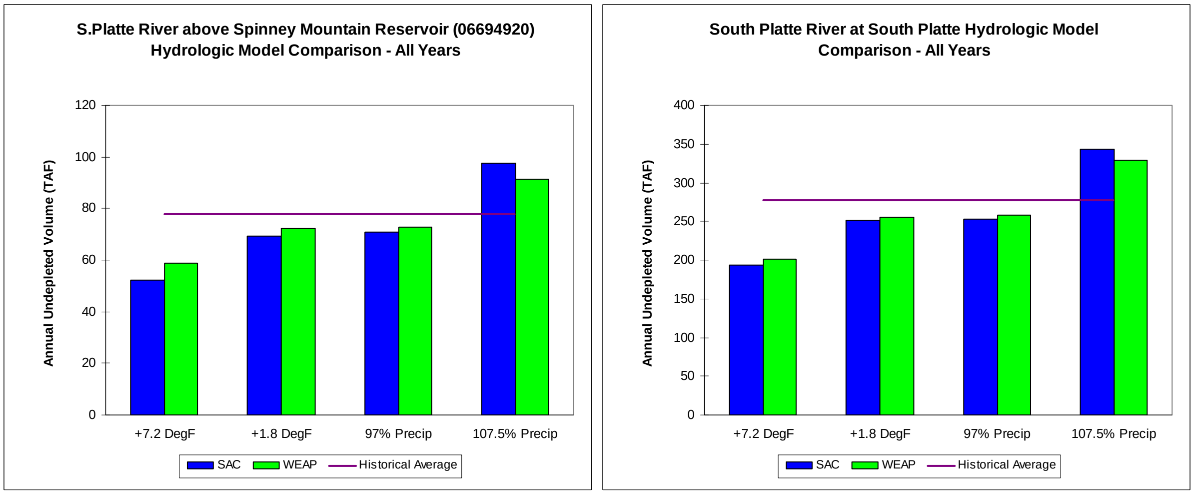
The Sacramento and WEAP models show similar responses to temperature increases. Both models show roughly similar changes in runoff volume under a modest 3% reduction in precipitation, while the Sacramento model simulated greater runoff volume than the WEAP model under the increased precipitation scenario.



Blue River below Dillon, CO (09050700) Hydrologic Model Comparison - All Years

Colorado River near Cameo (09095500) Hydrologic Model Comparison - All Years

Figure 3.1 Sensitivity of average annual volume to precipitation and temperature change - Blue below Dillon, Colorado near Cameo



S.Platte River above Spinney Mountain Reservoir (06694920) Hydrologic Model Comparison - All Years

South Platte River at South Platte Hydrologic Model Comparison - All Years

Figure 3.2 Sensitivity of average annual volume to precipitation and temperature change – South Platte above Spinney, South Platte at South Platte

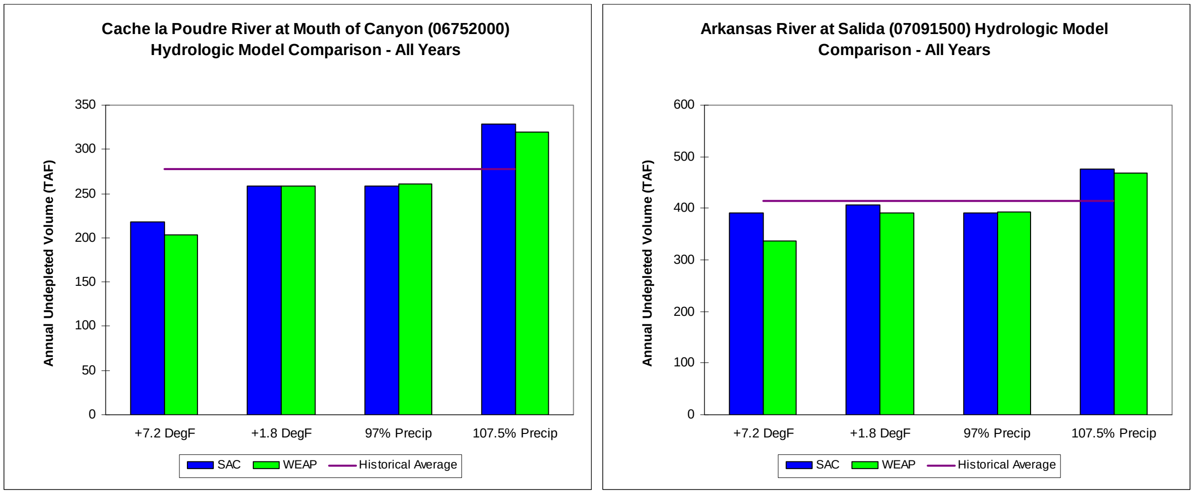


Figure 3.3 Sensitivity of average annual volume to precipitation and temperature change - Cache la Poudre at Mouth of Canyon, Arkansas at Salida

Figure 3.4 presents the average monthly streamflow volume results for each of the sensitivity simulations and the simulated baselines from each hydrologic model. The simulated baselines are computed for the historical period 1950 through 2005. For the 7.2^{o}F scenario, both models simulate fairly dramatic shifts in the timing of runoff, with the peak shifting a month earlier. One notable difference between the Sacramento and WEAP simulations for the 7.2^{o}F scenario is in the month of April, where WEAP simulates a much greater runoff volume when compared with the Sacramento model. In the WEAP model, the substantial warming leads to earlier runoff, but the ET is still energy limited due to the relatively short days and limited solar insolation in the early spring. In the Sacramento model the increase in PET is combined with an increase in soil moisture due to earlier snowmelt, resulting in an increase in the simulated AET in the early spring and less runoff in April. Although both of these factors are active in each model, the model formulations appear to result in a different emphasis being applied.

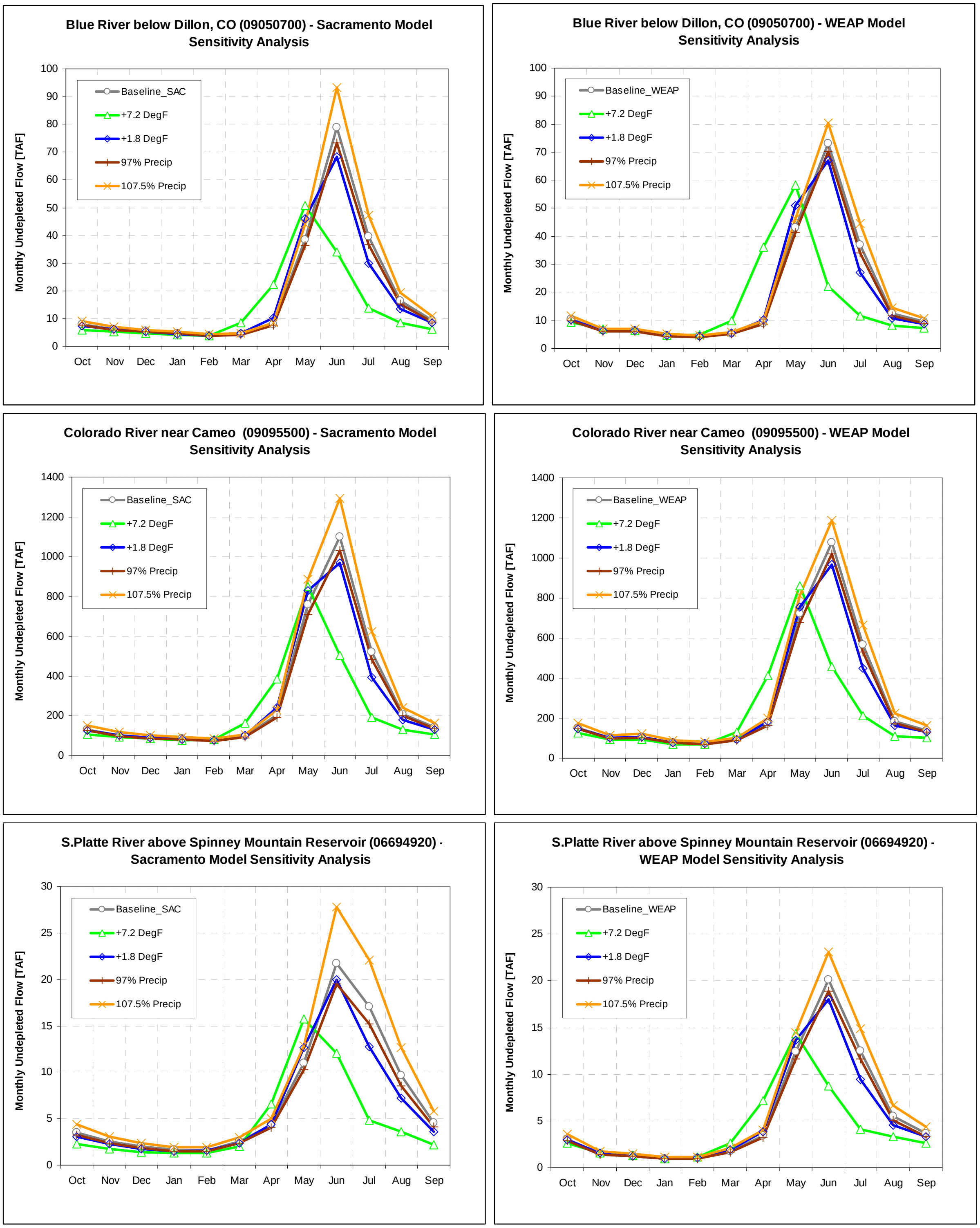
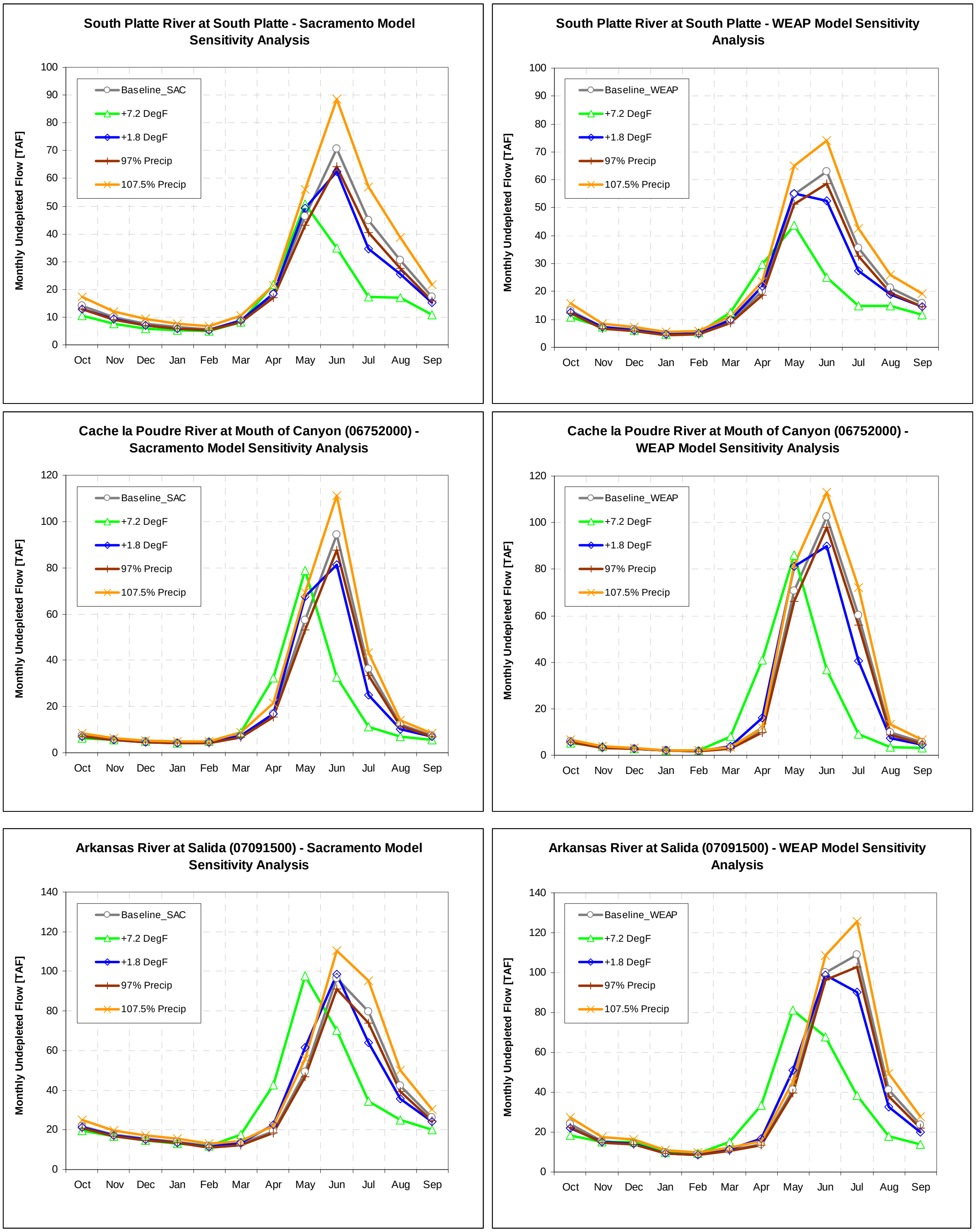


Figure 3.4 Sensitivity of monthly volume to precipitation and temperature change (continued)


South Platte River at South Platte - Sacramento Model Sensitivity Analysis

South Platte River at South Platte - WEAP Model Sensitivity Analysis

Cache la Poudre River at Mouth of Canyon (06752000) - Sacramento Model Sensitivity Analysis

Cache la Poudre River at Mouth of Canyon (06752000) - WEAP Model Sensitivity Analysis

Arkansas River at Salida (07091500) - Sacramento Model Sensitivity Analysis

Arkansas River at Salida (07091500) - WEAP Model Sensitivity Analysis

Figure 3.4 (continued)

Figure 3.5 shows the change in timing of runoff for the selected uniform temperature and precipitation change scenarios. The change in timing is computed here as the number of days earlier that the center of mass of runoff occurs between the baseline and climate adjusted simulations. The 7.2° F scenario leads to earlier runoff on the order of 15 to 25 days. The WEAP model tends to accentuate the shift toward earlier runoff in this case, as melt water tends to runoff instead of evapotranspire, as noted previously. The method used to calculate the change in timing is discussed under Runoff Timing in the *GCM-Based Streamflow Sensitivity* section, below.

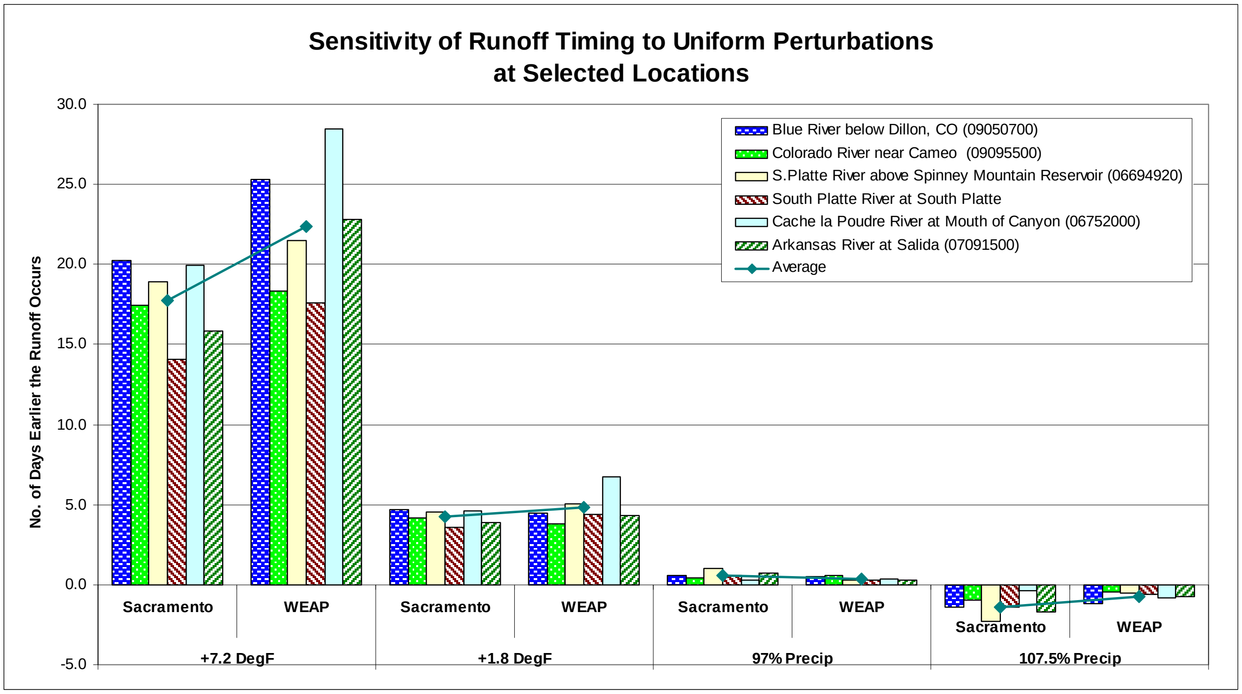


Figure 3.5 Sensitivity of Runoff Timing to Uniform Temperature and Precipitation Perturbations

Several observations from the simple sensitivity runs include:

- The simulated responses of the models are consistent with expectations regarding the direction and magnitude of runoff changes in response to temperature increases and precipitation increases and decreases, e.g. temperature increases lead to earlier runoff and decreased total streamflow volume.
- The changes resulting from temperature increase include both a reduction in total annual volume (seen in the annual volume plots as well) and a shift in timing of the runoff peak.
- The simulated change in annual volume to a temperature increase was greatest for the South Platte, and smallest for the Arkansas for both models.
- The sensitivity of annual volume to precipitation change appears to be nearly uniform among all basins, although it might be slightly higher for the South Platte.
- The reduction in total runoff volume from the 1.8^{o}F increase in temperature was roughly similar to the reduction in runoff from a 3% reduction in precipitation for both models.
- The Sacramento model tended to produce less runoff under the 7.2^{o}F scenario when compared with the WEAP model, except in the Arkansas Basin. For both models the

reduction in volume and shift in runoff timing is quite dramatic under the 7.2°F scenario.
- The timing of peak runoff is later when precipitation increases and earlier when precipitation decreases, but these shifts are minor.

These results provide an initial indication of the expected trends in simulated annual runoff volume and timing as a result of changes in precipitation and temperature inputs.

GCM-BASED STREAMFLOW SENSITIVITY RESULTS (STAGE 2)

The ten GCM-Based climate scenarios were used to modify the historical temperature and precipitation forcing data used by each hydrologic model. Streamflow generation is sensitive to both the temporal and spatial pattern of temperature and precipitation change, and the GCM-based scenarios explicitly represent these patterns. Table 3.1 summarizes these scenarios and includes the spatially averaged seasonal and annual average temperature and precipitation change for each of the future time periods, compared to the 1950-1999 baseline. Bold values are the average seasonal changes across months, and non-bold values are the high and low monthly value range. The seasons are defined as: Winter (December – February), spring (March – May), summer (June – August), and fall (September – November). All models show monthly, seasonal, and annual warming, though both the magnitude and timing of that warming vary. These variations are likely a result of the internal workings of the climate models and emission scenarios. Seasonal precipitation change varies across projections and future time horizons. The projections consistently depict wetter winters, with the exception of a slight decrease in the *2070 Hot & Wet* scenario.

Table 3.1 Seasonal temperature differences and precipitation percent changes

Average Seasonal Change – 2040

Temperature Increase (°F)

	Warm & Wet	Hot & Wet	Median	Warm & Dry	Hot & Dry
Winter	**1.4** (1-2)	**2.6** (2-3)	**2.9** (2-3)	**1.9** (1-3)	**4.0** (4-5)
Spring	**0.8** (0-1)	**4.0** (3-5)	**2.5** (1-4)	**2.1** (1-2)	**5.2** (5-6)
Summer	**2.1** (2-3)	**6.3** (6-7)	**4.5** (4-5)	**3.7** (3-4)	**6.0** (5-7)
Fall	**2.3** (1-3)	**4.1** (3-6)	**3.7** (2-5)	**3.1** (3-4)	**5.0** (4-6)
Annual	**1.6**	**4.2**	**3.4**	**2.7**	**5.0**

Precipitation Change (%)

	Warm & Wet	Hot & Wet	Median	Warm & Dry	Hot & Dry
Winter	**11.2** (-9 - +33)	**7.3** (+3 - +12)	**19.9** (+13 - +25)	**15.9** (+14 - +20)	**3.1** (-1 - +6)
Spring	**10.0** (+6 - +17)	**4.3** (-6 - +17)	**-6.2** (-17 - +2)	**-7.2** (-14 - +2)	**-6.4** (-30 - +22)
Summer	**10.7** (-10 - +21)	**3.3** (-1 - +9)	**-8.2** (-17 - +2)	**-13.2** (-21 - -4)	**-18.8** (-32 - -12)
Fall	**14.1** (+1 - +23)	**0.4** (-10 - +6)	**8.5** (-9 - +31)	**-8.8** (-15 - +2)	**-10.9** (-18 - +1)
Annual	**11.4**	**3.8**	**2.6**	**-3.7**	**-8.5**

(continued)

Table 3.1(Continued)

Average Seasonal Change – 2070

Temperature Increase (°F)

	Warm & Wet	Hot & Wet	Median	Warm & Dry	Hot & Dry
Winter	**3.5**	**5.2**	**4.6**	**4.3**	**5.6**
	(3-4)	(4-7)	(3-6)	(3-5)	(4-6)
Spring	**3.8**	**6.5**	**4.5**	**4.1**	**5.9**
	(3-4)	(6-7)	(3-6)	(3-4)	(5-7)
Summer	**4.2**	**7.5**	**5.6**	**5.3**	**11.4**
	(4-5)	(7-8)	(5-6)	(5-6)	(11-12)
Fall	**4.2**	**6.2**	**5.6**	**5.1**	**9.3**
	(2-5)	(4-8)	(4-7)	(4-6)	(8-12)
Annual	**3.9**	**6.4**	**5.1**	**4.7**	**8.1**

Precipitation Change (%)

	Warm & Wet	Hot & Wet	Median	Warm & Dry	Hot & Dry
Winter	**12.0**	**-3.2**	**20.6**	**15.7**	**13.8**
	(-4 - +12)	(-8 - +3)	(+9 - +28)	(0 - +26)	(+9 - +17)
Spring	**1.8**	**1.4**	**-8.7**	**-4.2**	**-2.7**
	(-5 - +16)	(-10 - +9)	(-22 - +3)	(-16 - +14)	(-16 - +15)
Summer	**24.5**	**20.8**	**-2.6**	**4.6**	**-25.2**
	(+9 - +37)	(+12 - +31)	(-4 - -1)	(0 - +9)	(-48 - -8)
Fall	**7.8**	**0.0**	**-4.3**	**-16.0**	**-9.5**
	(+4 - +13)	(-19 - +15)	(-5 - -3)	(-29 - -6)	(-11 - +5)
Annual	**10.8**	**4.9**	**0.4**	**-0.1**	**-5.9**

*Values in parentheses represent the range of changes encountered in the monthly data.

The average annual undepleted streamflow volume was computed for each climate change scenario and for both hydrologic models, with the results presented in Figure 3.6 through Figure 3.11 at the six selected locations. A horizontal line depicts the historical average annual undepleted streamflow volume. Note that the scale of the y-axis is unique for each station.

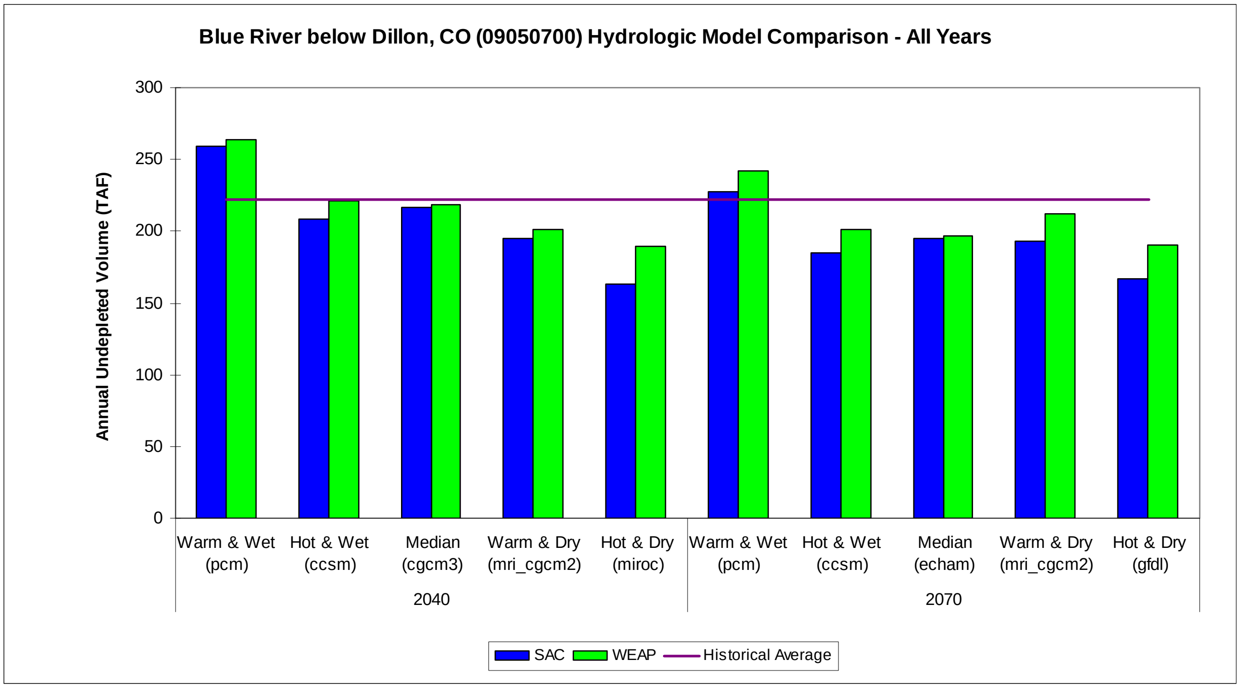


Figure 3.6 Average annual volume change for all climate change simulations – Dillon

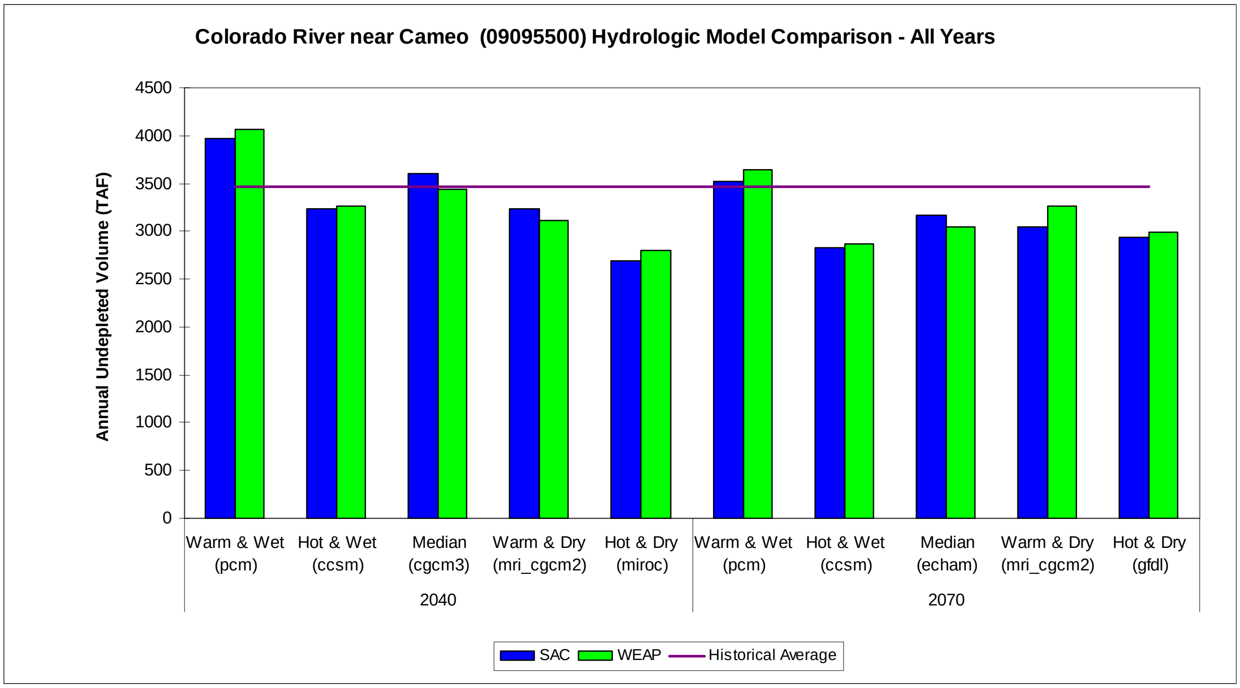


Figure 3.7 Average annual volume change for all climate change simulations - Cameo

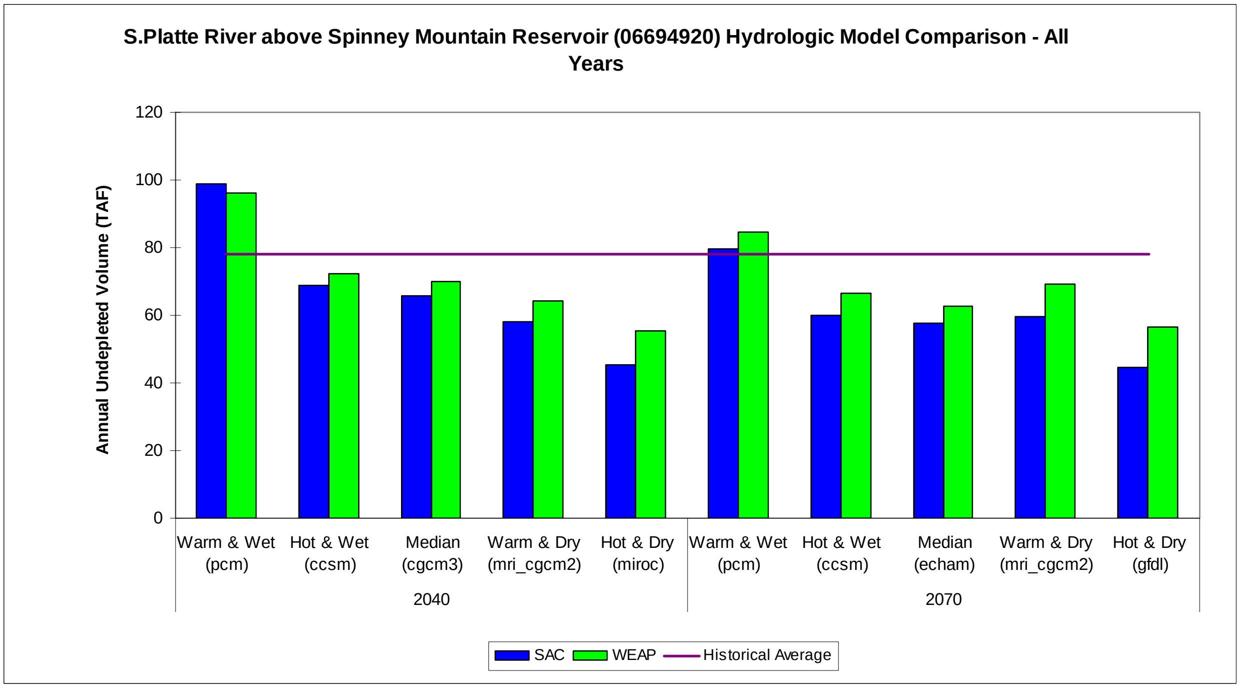


Figure 3.8 Average annual volume change for all climate change simulations - Above Spinney.

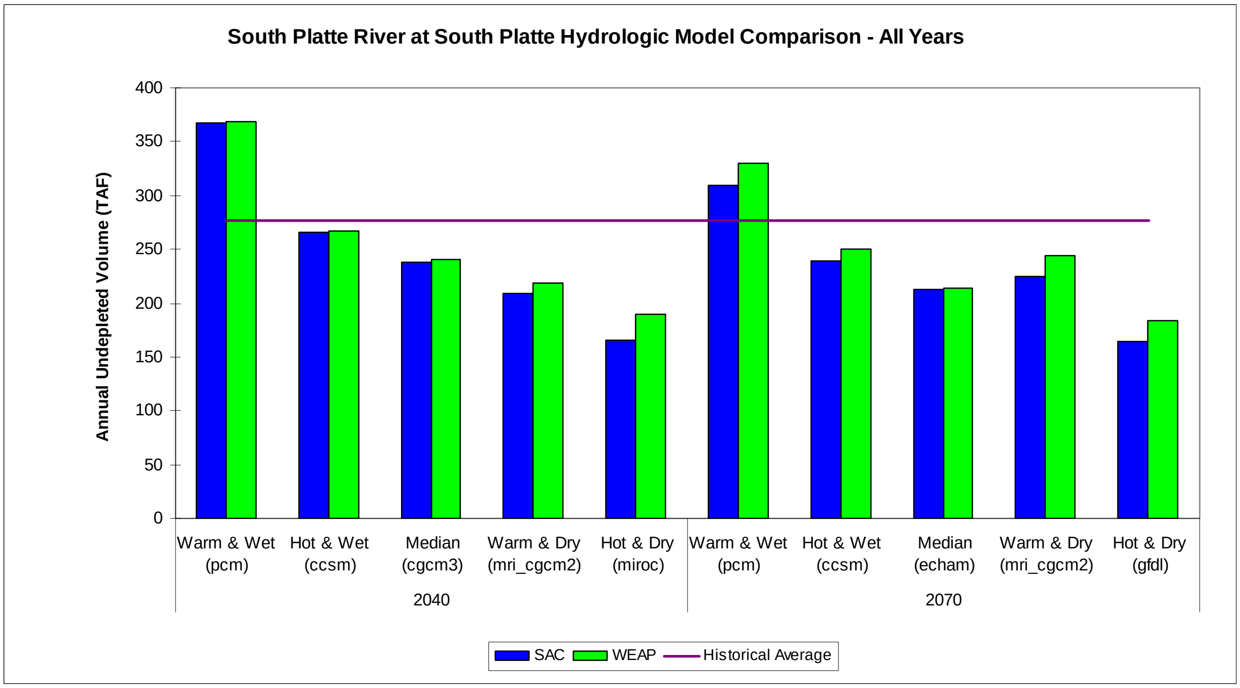


Figure 3.9 Average annual volume change for all climate change simulations - South Platte

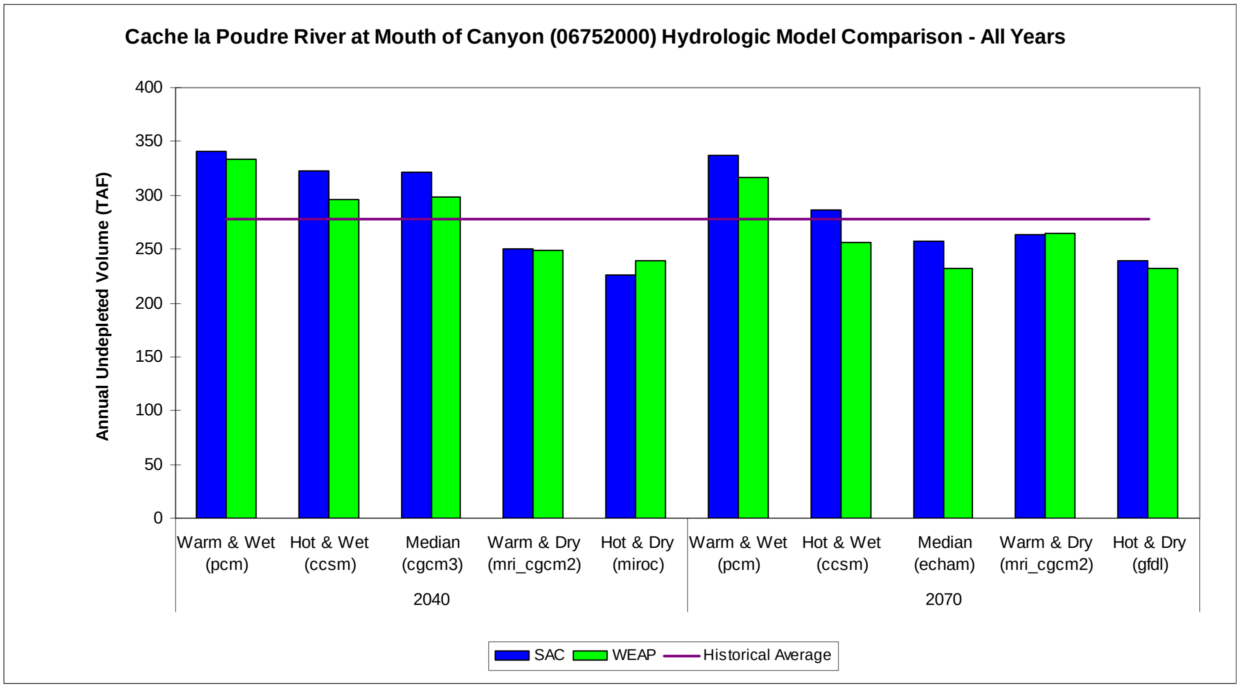


Figure 3.10 **Average annual volume change for all climate change simulations - Cache la Poudre**

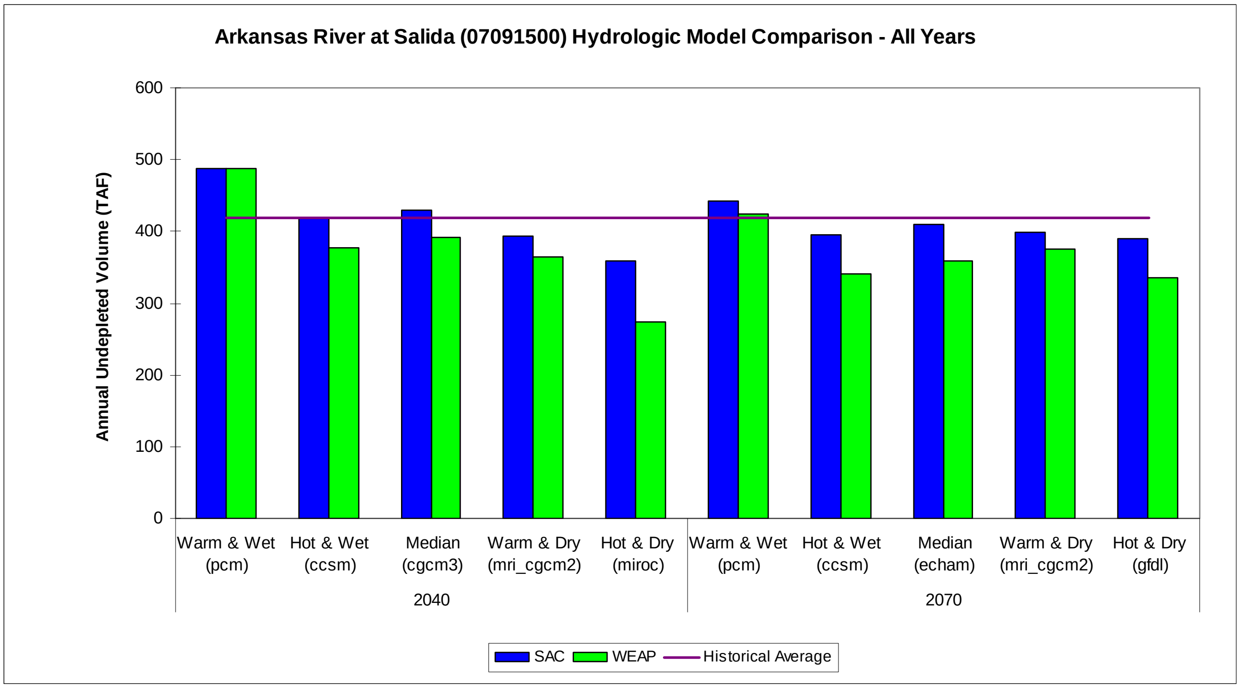


Figure 3.11 **Average annual volume change for all climate change simulations – Salida**

The figures show that only one of the ten scenarios consistently results in an increase in total streamflow volume across all the watersheds and for both models (e.g. *2040 Warm & Wet*). The *2040 and 2070 Hot & Dry and Warm & Dry* scenarios all show declines in total annual volume, but at many locations the decline is greater for 2040 than for 2070, as discussed further on page 86. The *2040 Median* and the *2040 Hot & Wet* scenarios suggest a more complex, spatial climate-change pattern. The *2040 Median* scenario shows little to no change in simulated runoff for the Colorado and Arkansas Basins, decreased runoff in the South Platte Basins, and increased runoff in the Poudre Basin. The *2040 Hot & Wet* scenario yields declines in simulated annual runoff from all basins except the Poudre. Figure 3.12 and Figure 3.13 depict the spatial pattern of precipitation change on an annual basis for the *2040 Median* and the *2040 Hot & Wet* scenarios. Within the study area the *2040 Median* shows a strong southeast-northwest, dry to wet gradient, while the *2040 Hot & Wet* scenario shows an opposite precipitation gradient (e.g. a drier southwest and wetter northeast).

The wetter scenarios suggest a modest increase in total precipitation, with corresponding increases in simulated runoff in many cases. For example, all of the *Warm & Wet* scenarios show increased runoff, while there is an overall decline in runoff under the *2040 Hot & Wet* scenario, as the increased evapotranspiration from warming dominates the modest precipitation increase, except in the Poudre Basin (Figure 3.10). Increased winter precipitation is the most optimistic finding for water providers, as snowpack is the primary mechanism of water storage across the Colorado Rockies, with providers relying on it as the primary water source to maintain reservoir levels and to aid in late summer flows. Perhaps most notable among the scenarios is that both the *2040 and 2070 Hot & Dry* scenarios are wetter in the winter, with overall drying attributable to less precipitation in the spring, summer, and fall seasons.

The *2070 Hot & Wet* and the *2070 Hot & Dry* revealed interesting results in terms of both spatial and temporal variability of precipitation. The "wet" characteristic of the *2070 Hot & Wet* scenario is primarily due to *increased* summertime precipitation, while the "dry" characteristic of the *2070 Hot & Dry* scenario is largely attributable to a *decrease* in summer precipitation (see Figure 2.5). The Colorado at Cameo location (Figure 3.7) shows that the total annual runoff volume in the *2070 Hot & Wet* scenario is actually less than the *2070 Hot & Dry* scenario, largely an outcome of timing and spatial distribution of precipitation change, as winter precipitation is greater in the later scenario, particularly over the western portion of the basin (see Figure 2.5, Figure 3.14 and Figure 3.15). The *2070 Hot & Wet* and *2070 Hot & Dry* scenarios exhibit strong spatial pattern of precipitation change, although opposite in direction. The *2070 Hot & Wet* scenario reveals wet to the east and drying to the west, while the *2070 Hot & Dry* scenario shows a strong east-west gradient, with substantially more drying in the east, with some increases in annual precipitation, most notably over the Colorado Basin.

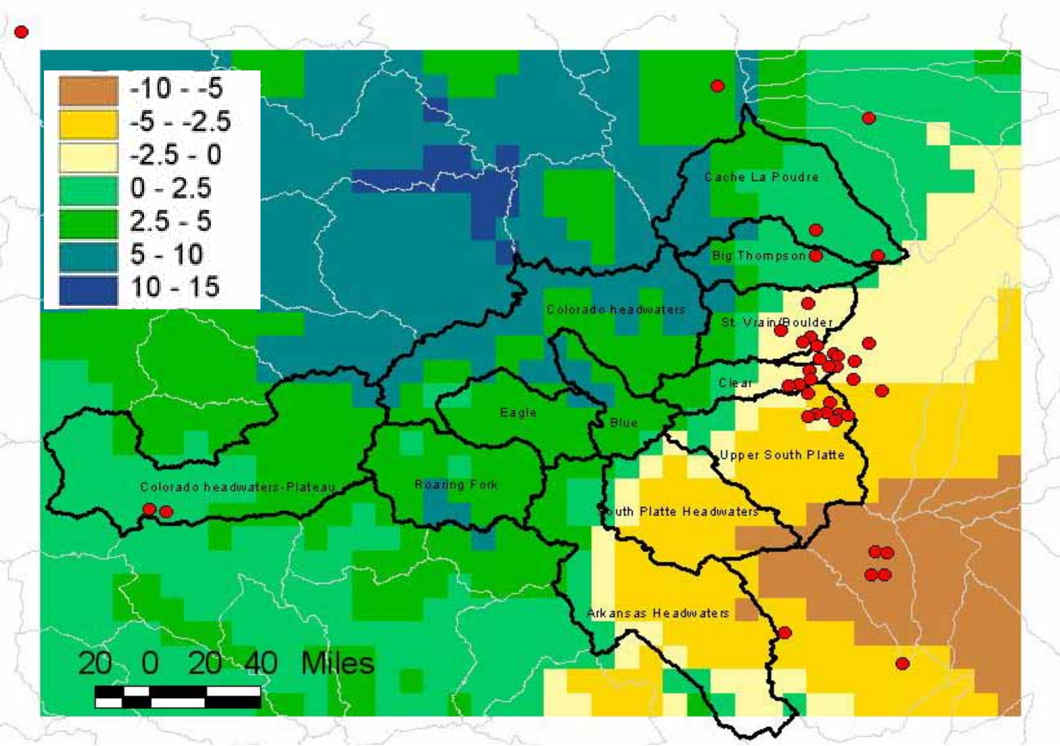


Figure 3.12 Percent change in total annual average precipitation between the historical period (1950 to 2000) and the 2040 period (2025 to 2054) for the *2040 Median* scenario (cgcm3_1.2 B1)

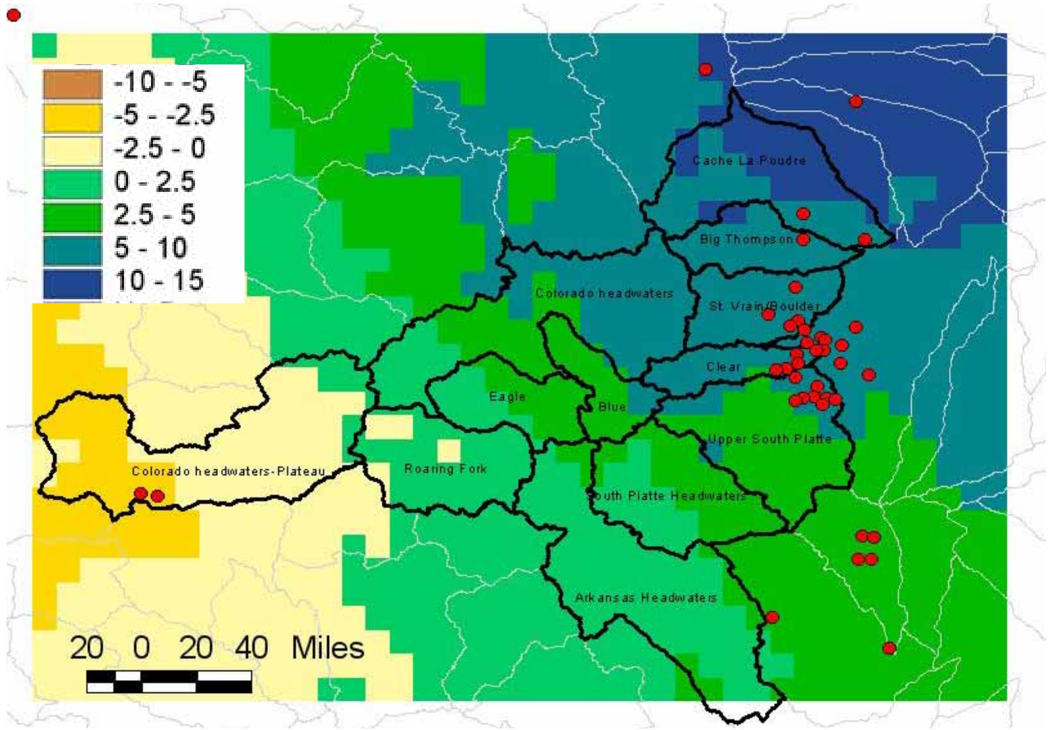


Figure 3.13 Percent change in total annual average precipitation between the historical period (1950 to 2000) and the 2040 period (2025 to 2054) for the *2040 Hot &Wet* scenario (ccsm3_0.2.sresa1b)

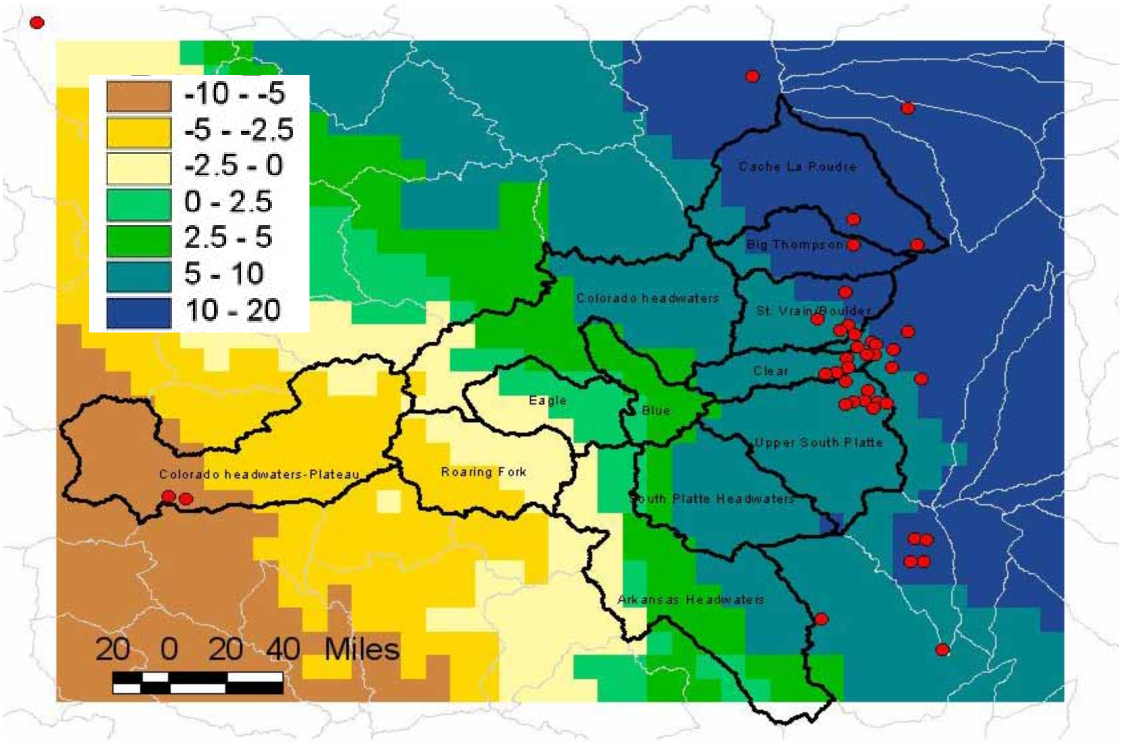


Figure 3.14 Percent change in total annual average precipitation between the historical period (1950 to 2000) and the 2070 period (2055 to 2084) for the 2070 Hot &Wet scenario

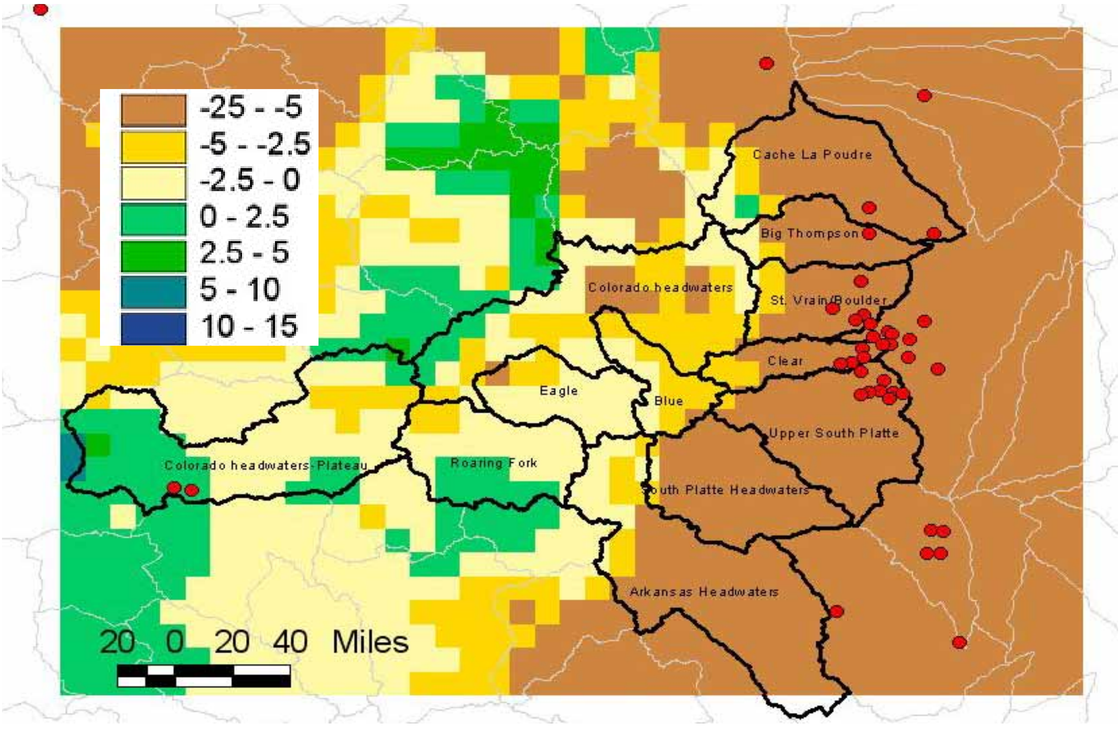


Figure 3.15 Percent change in total annual average precipitation between the historical period (1950 to 2000) and the 2070 period (2055 to 2084) for the *2070 Hot & Dry* scenario

AVERAGE MONTHLY SIMULATED STREAMFLOW

In addition to annual volume, average monthly simulated streamflow volumes were computed for each climate change scenario and for both hydrologic models. These results are summarized for the six representative locations for 2040 scenarios in Figure 3.16 and the 2070 scenarios in Figure 3.17. The gray line is the average simulated baseline for each model using the unadjusted, historical climate sequence. Note that the scale of the y-axis is unique for each station.

There are some general observations regarding the sensitivity of simulated streamflow under the climate change scenarios for both the Sacramento and WEAP models. While both are continuous, lumped parameter models, the Sacramento and WEAP models differ in several of their process formulations (e.g. the soil moisture and snowmelt algorithms as examples). This fact gives rise to fundamental differences in their characterization of streamflow response to climate change. The Sacramento model tends to produce greater evaporative losses in mid-winter and late spring under warming when compared with the WEAP model. Likewise, the WEAP model tends to yield greater springtime flows under warmer conditions. Combined, these differences tend to make WEAP a less sensitive model to temperature perturbations than the Sacramento model using the PET response procedure formulated for this study.

The WEAP model tends to be less sensitive to warming in terms of streamflow reduction, with the most notable difference between the models in the month of April. It appears that warmer spring conditions tend to mobilize surface runoff more in the WEAP model than in the Sacramento model, and while simulated potential ET is higher in the future relative to the historical climate, the increase is low relative to the summer months simply due to the smaller insolation in April. In addition, relatively low soil moisture conditions heading into April tend to favor surface and sub-surface runoff instead of ET, thus actual simulated ET remains relatively low and the melt water tends to runoff. In the Sacramento Model, losses in the late and early spring tend to increase as a result of the increased potential for ET associated with higher temperatures. The increased potential corresponds with increases in available soil moisture due to earlier snowmelt and the fact that the Sacramento model first simulates the filling of tension water zones prior to simulating snowmelt runoff, allowing more of the increased potential ET to be realized. The Sacramento Model also tends to estimate higher ET loss in mid-winter than does the WEAP model because it simulates some loss from forest-covered areas even when the ground is snow covered.

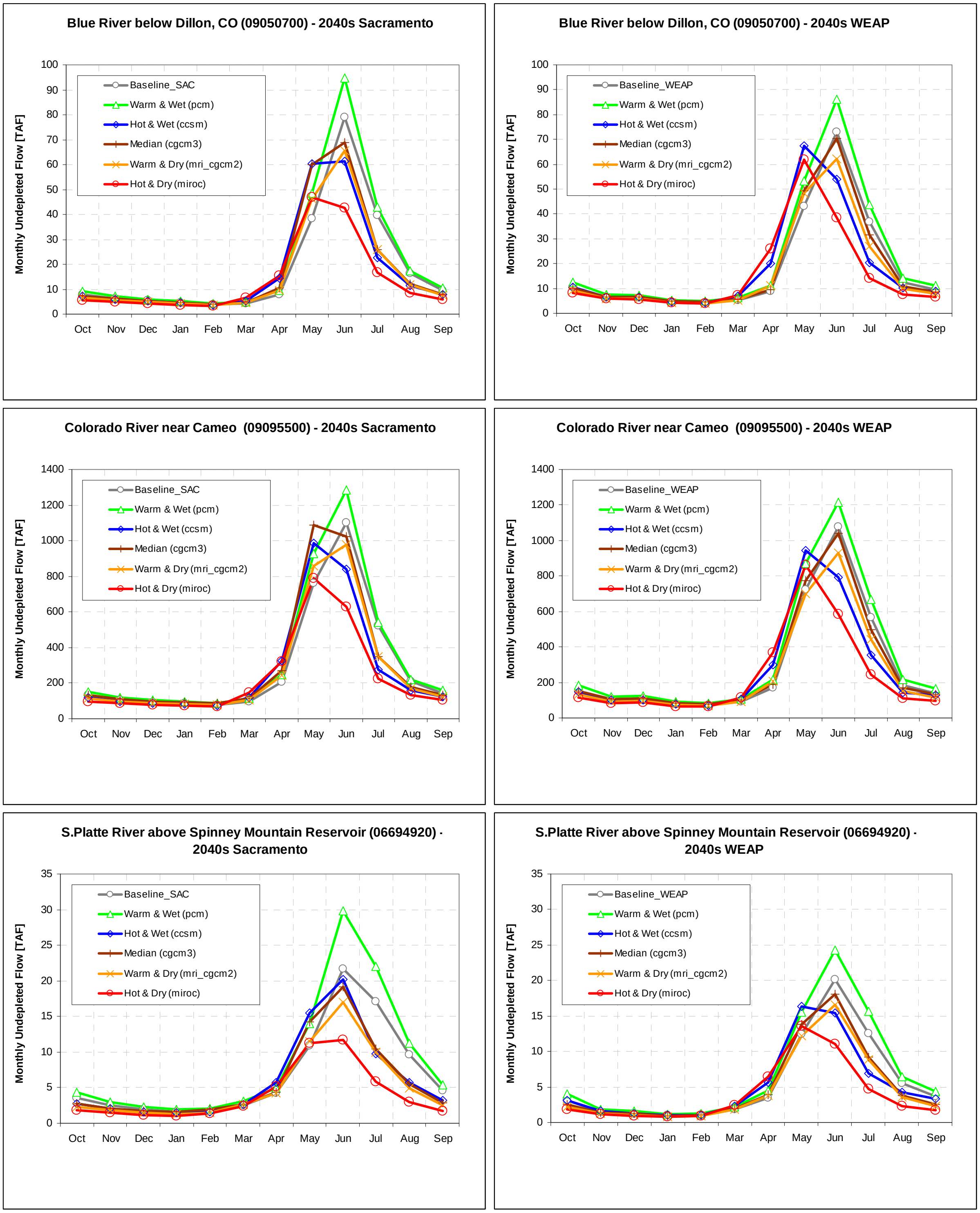


Figure 3.16 Simulated average monthly streamflow volume for the 2040 scenarios (continued)

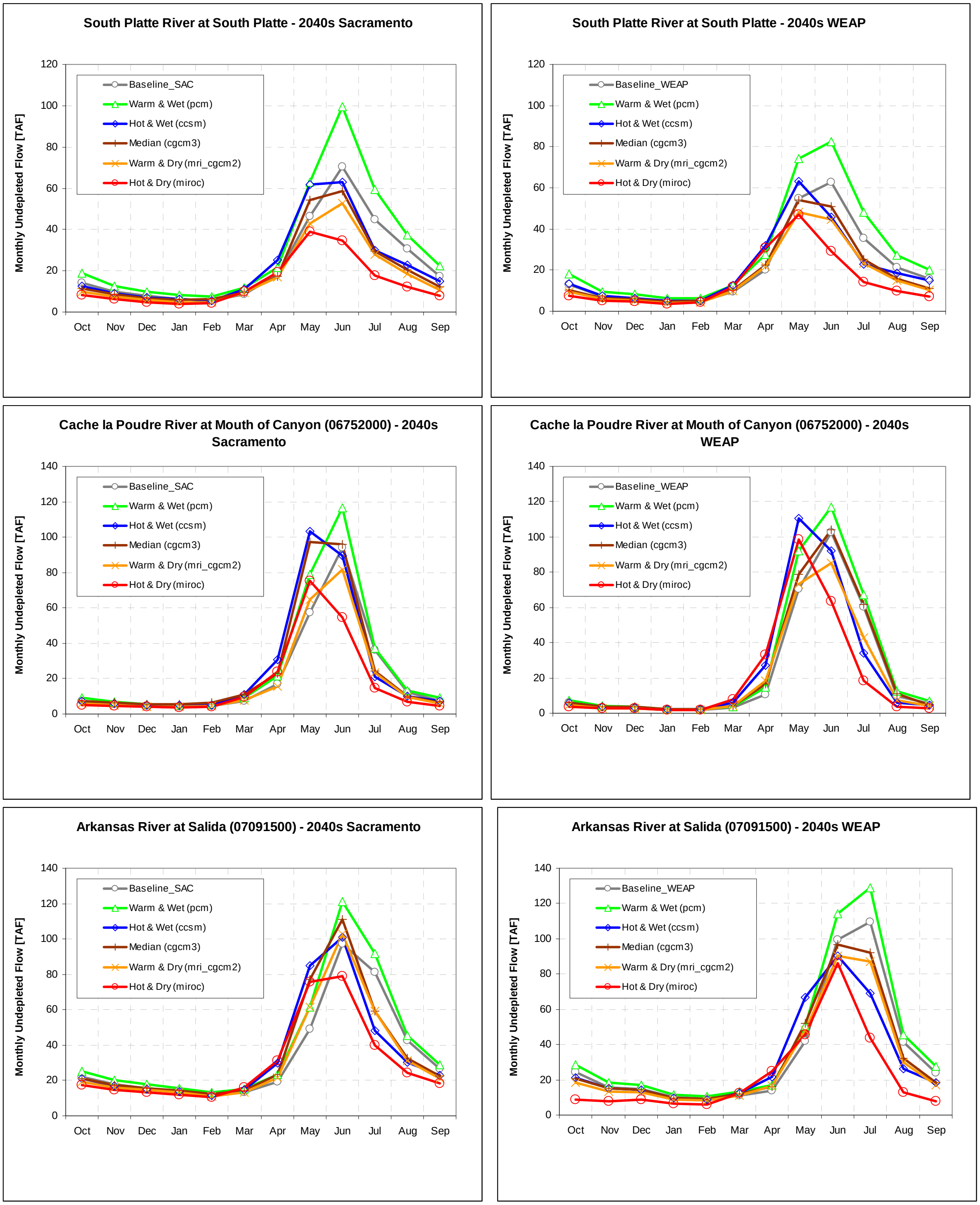


Figure 3.16 (continued)

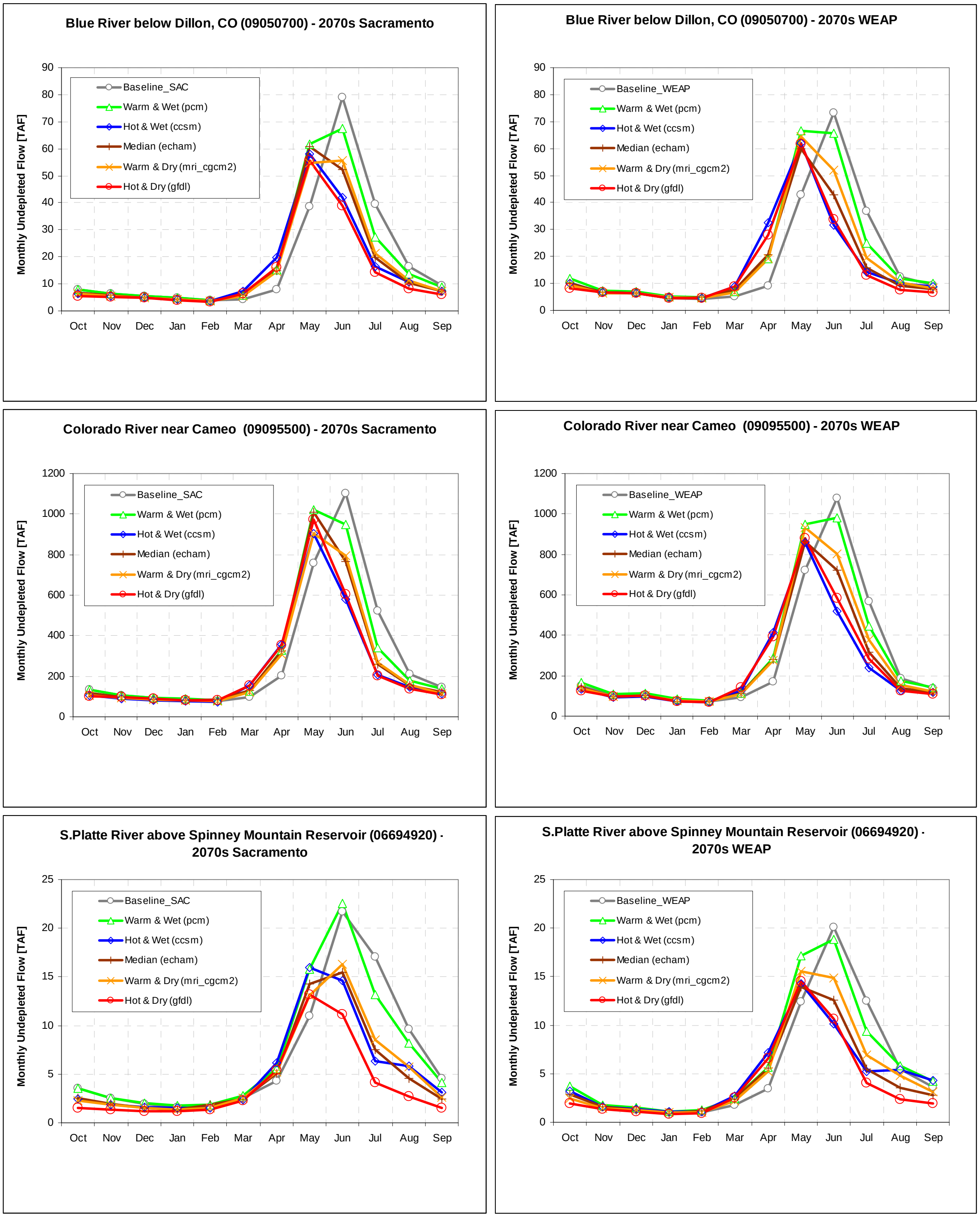


Figure 3.17 Simulated average monthly streamflow volume for the 2070 scenarios (continued)

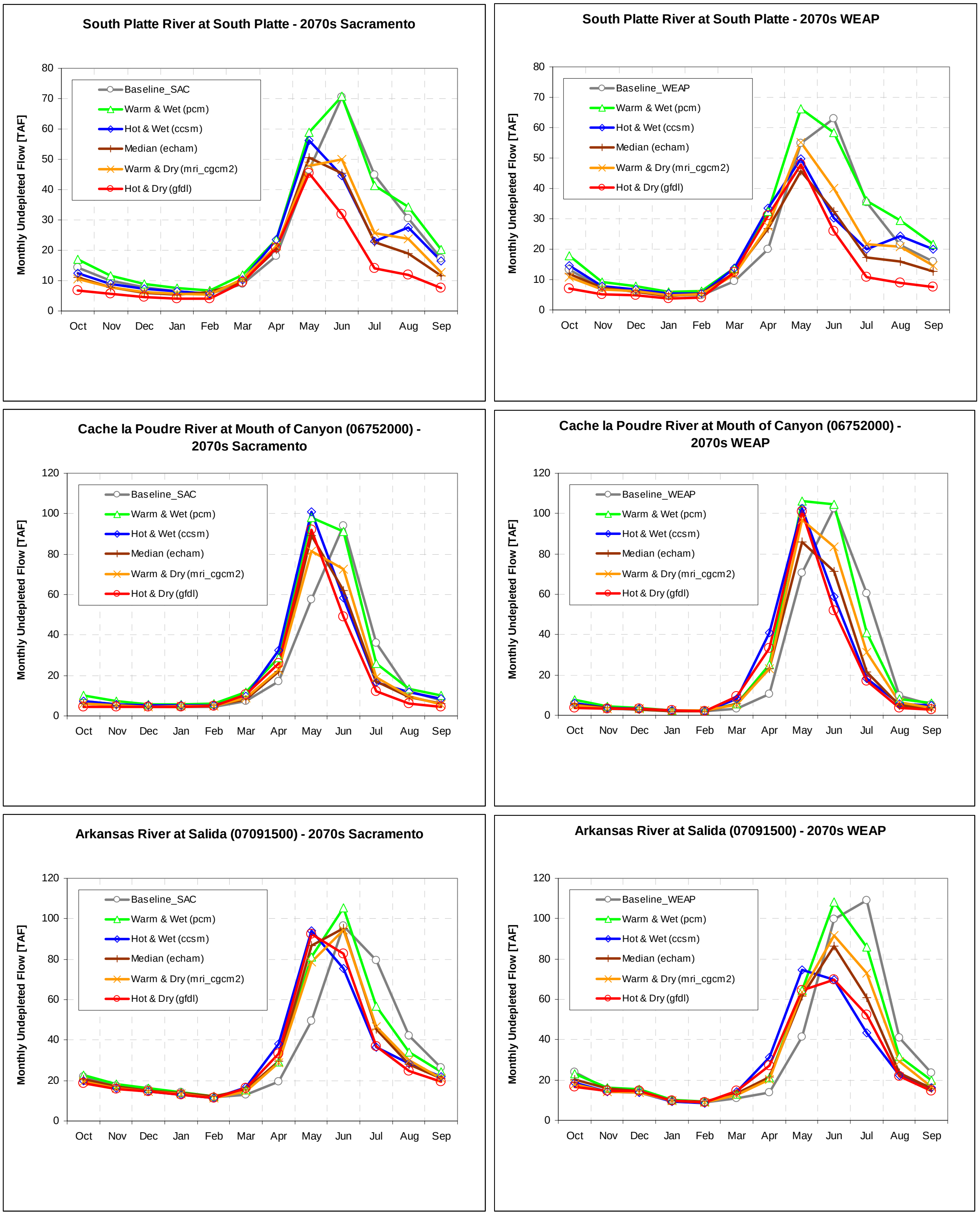


Figure 3.17 (continued)

RUNOFF TIMING

Runoff timing is important when considering the availability of water during times of peak demand as well as in making structural and operational plans for managing storage. Changes in timing can also impact the value of water rights in relation to available storage and demand.

It is expected that the results of this study, including projected changes in runoff quantity and timing, will be used to drive water allocation and planning models, allowing the impact of the range of GCM projections and associated hydrologic model results simulated in this study to be included in the planning process. Runoff timing was calculated for each modeled scenario using a center-of-mass technique. This technique computes the day of the year that represents the temporal center of mass of annual runoff, with equal runoff volume before and after the computed date. Shape differences in the hydrograph influence the center of mass, showing the effects of:

- Earlier snowmelt due to increased temperatures in the selected GCMs,
- Increase in ET based on reduced snow cover, and
- Differences in response to individual precipitation events.

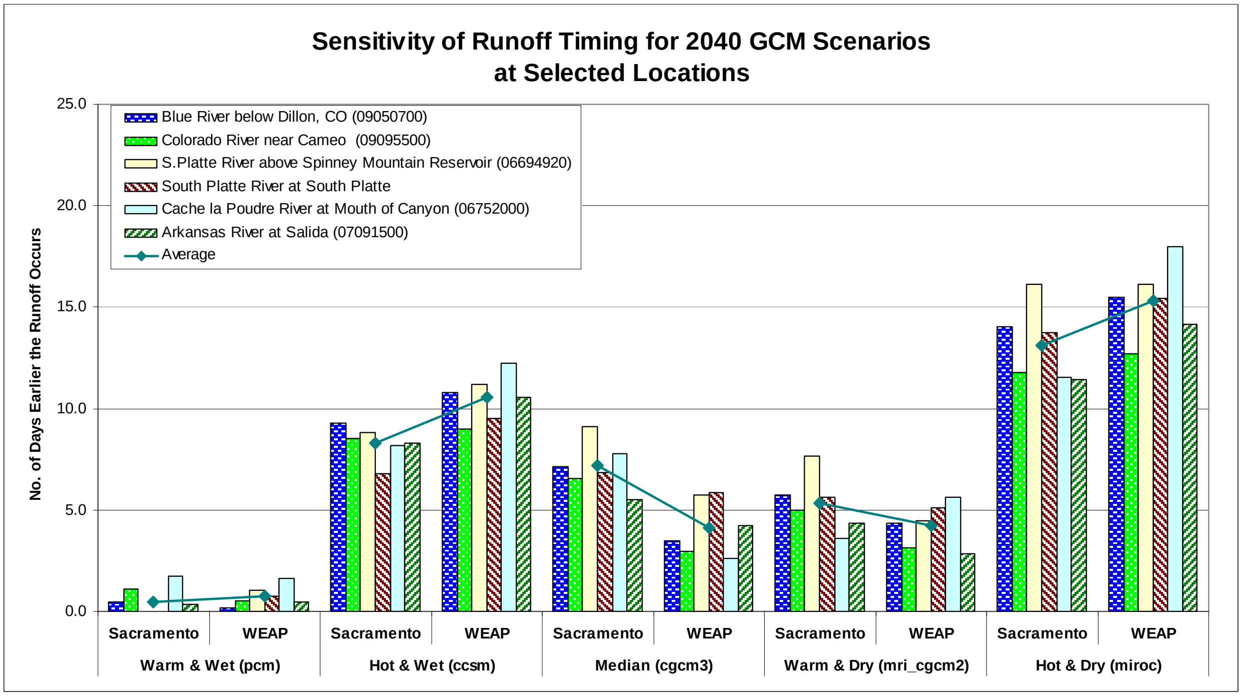
For all the studied alternatives, the selected GCMs consistently indicate an increase in temperature, although they differ in the seasonal distribution of that temperature increase. Table shows the range of simulated average annual changes to runoff timing at selected points for each model for each future time period. With one exception, which is associated with the *2040 Warm & Wet* Sacramento model simulation on the South Platte, both the WEAP and Sacramento models simulate earlier runoff.

Table 3.2 Change in Runoff Timing for two future periods, showing the range and variability of timing changes by location and model. Change is reported in number of days, with positive numbers indicating earlier runoff.

2040 Location	Sacramento Model		WEAP Model	
	Maximum	Minimum	Maximum	Minimum
Blue River below Dillon	14.0	0.5	15.5	0.2
Colorado River near Cameo	11.8	1.1	12.7	0.5
South Platte River above Spinney Mountain Reservoir	16.1	-0.8	16.1	1.1
South Platte River at South Platte	13.7	-0.1	15.4	0.8
Cache la Poudre River at Mouth of Canyon	11.5	1.7	18.0	1.6
Arkansas River at Salida	11.4	0.4	14.1	0.5

2070 Location	Sacramento Model		WEAP Model	
	Maximum	Minimum	Maximum	Minimum
Blue River below Dillon	16.2	7.9	19.3	8.6
Colorado River near Cameo	14.6	7.6	15.6	6.3
South Platte River above Spinney Mountain Reservoir	18.4	6.1	18.2	7.5
South Platte River at South Platte	13.5	4.4	17.8	4.1
Cache la Poudre River at Mouth of Canyon	14.2	8.0	21.0	10.5
Arkansas River at Salida	12.4	7.0	18.0	7.2

Figure 3.18 presents the simulated change in runoff timing for selected locations for both hydrologic models and both future periods. The average value for the six basins is indicated for each hydrologic model, with a line drawn between them to highlight the comparison between models. The simulated runoff timing between the two models and among basins is similar, while differences between GCM projections are more prominent. Differences between the two future time periods suggest a uniform shift toward earlier runoff that reflects the trend toward warming in the later period. Consistent with the results of the simple sensitivity assessment, temperature changes appear to dominate the impact on timing, while the impact of precipitation is not apparent (i.e. “hot” models project the largest change in timing and “warm” models project the smallest changes).



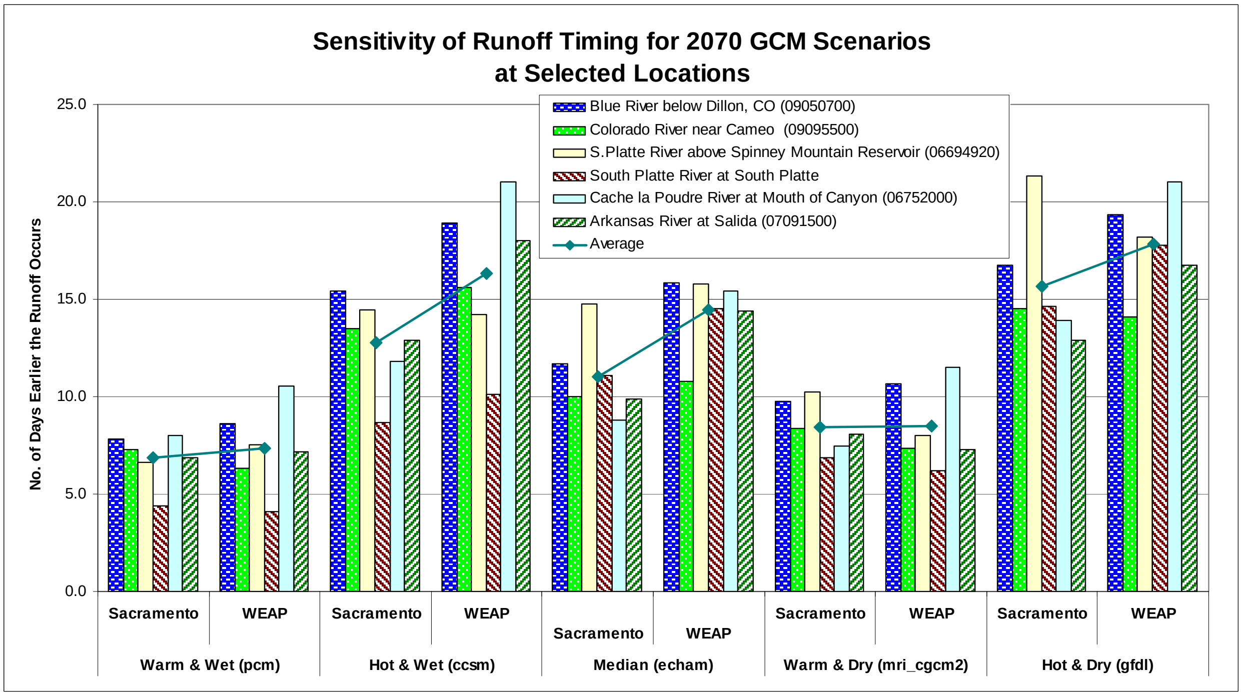


Figure 3.18 Shift in Simulated Runoff Timing – Selected Locations

Figure 3.19 presents scatter plots comparing the change in runoff timing between the WEAP and Sacramento models for six selected locations and for both 2040 and 2070 time periods. These figures show that, generally, for scenarios in which the shift in runoff timing is small, the Sacramento model simulates a larger shift than the WEAP model, and when the number of days earlier is large, the reverse is true, with the WEAP model simulating larger differences than the Sacramento model. This pattern is consistent for all study points, although individual responses to particular GCMs cause variations in the response of each model. A more subtle pattern identifiable in these plots is the greater variation between the two models for high-elevation watersheds (Dillon and Spinney) than for larger, lower elevation watersheds (Cameo and South Platte).

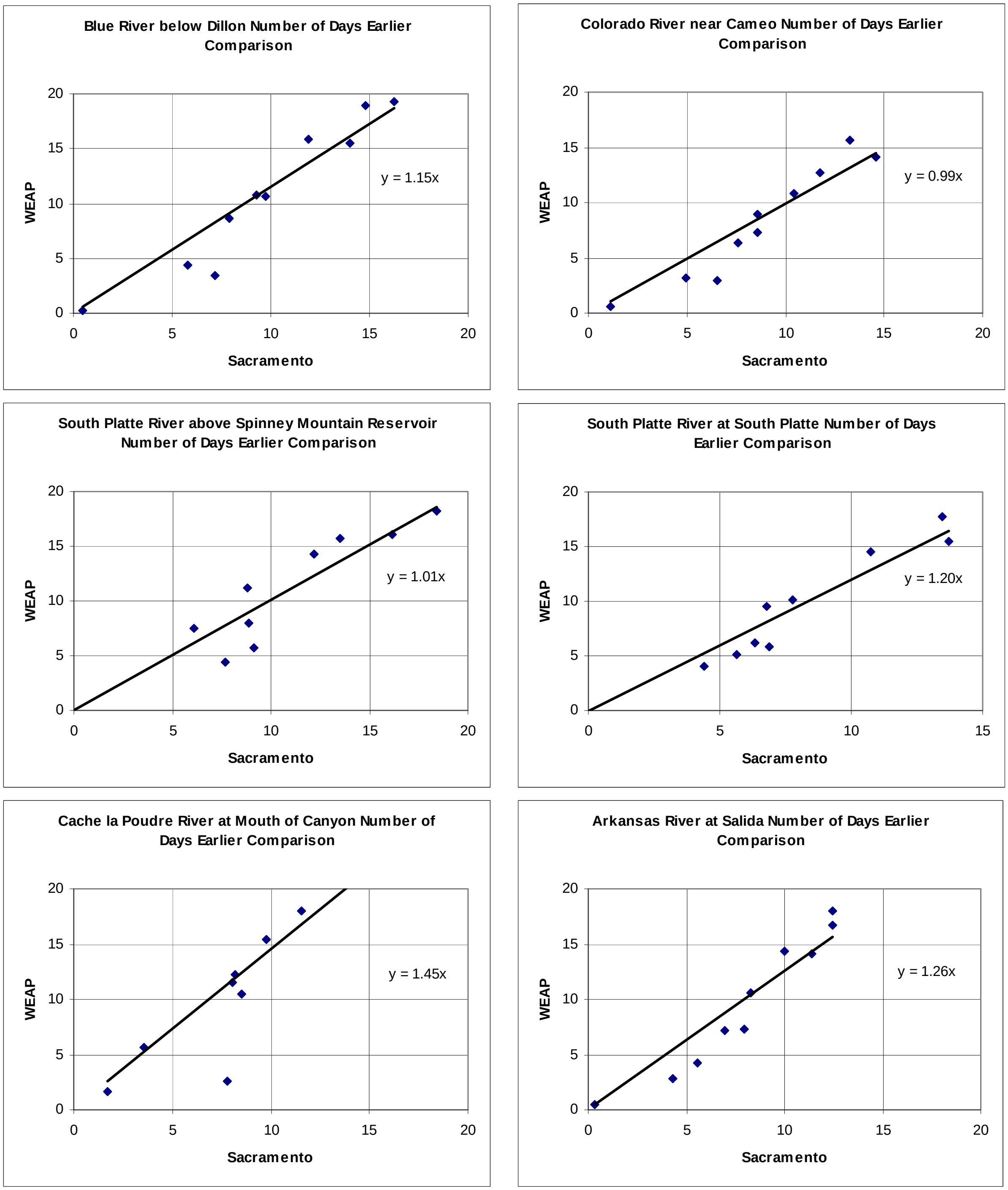


Figure 3.19 Runoff Timing Change Scatter Plot

COMPARISON OF 2040 AND 2070 PERIODS

Climate Model Response

A fundamental trend exhibited in all of the climate model projections is toward increased warming from the 2040 period to the 2070 period. This trend was clear from the outset of this study when the decision was made to assess the impact on streamflow for both time periods. Moving from 2040 to 2070, there was no obvious trend toward either more or less precipitation. Both time periods showed a wide range of precipitation changes among the GCM projections. The temperature and precipitation changes from the baseline period to 2040 and 2070 are illustrated in Figure 3.20. The temperature comparison is indicated in absolute change, in degrees F, while precipitation is indicated as a percent change. The temperature change almost doubles in moving from the 2040 to the 2070 period. The precipitation increases in three of the five projections, and does so in both future periods.

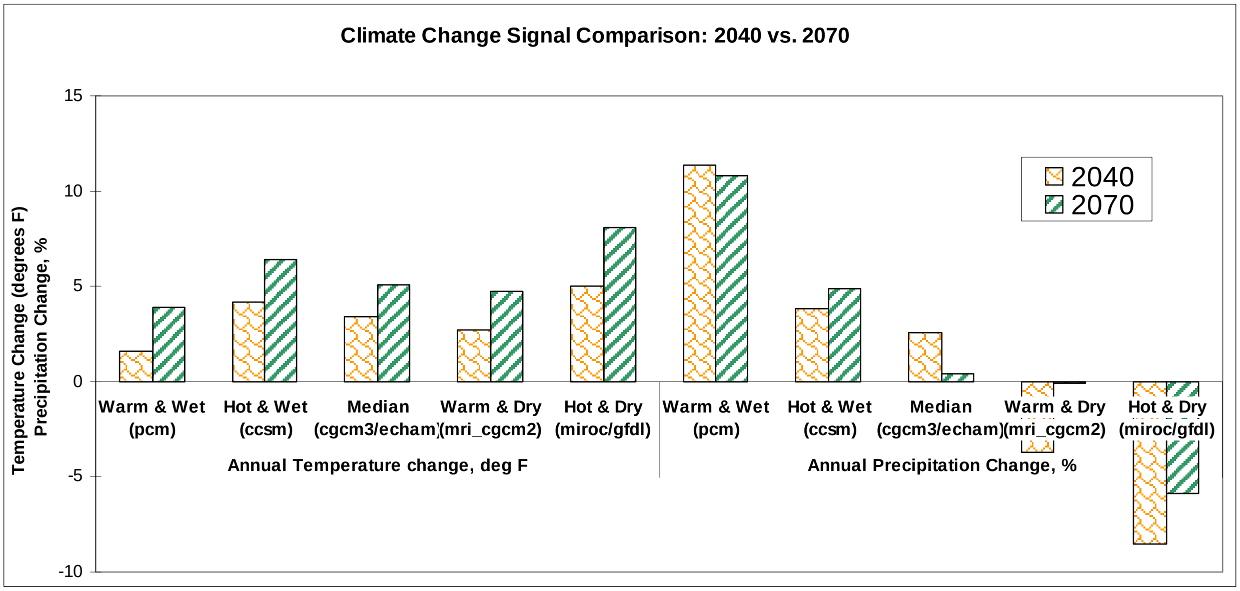


Figure 3.20 Comparison of Temperature and Precipitation Change for 2040 and 2070 Periods

Average annual changes are indicators of hydrologic response, but the seasonal distribution of the change may also have an important impact. Figure 3.21 and Figure 3.22 show the seasonal temperature and precipitation changes exhibited by the selected climate models, allowing a comparison of the 2040 and 2070 periods. The increased warming between the periods is again evident, but it is notable that the 2070 hot & dry scenario is significantly hotter than the 2040 scenario in the summer and fall, while not much different in the winter and spring. The precipitation pattern changes significantly from the 2040 to the 2070 period, with four of the five models showing increased summertime precipitation between periods and in relation to the surrounding seasons. In contrast, the hot & dry scenario shows a further reduction in summer precipitation, while winter precipitation increases quite dramatically.

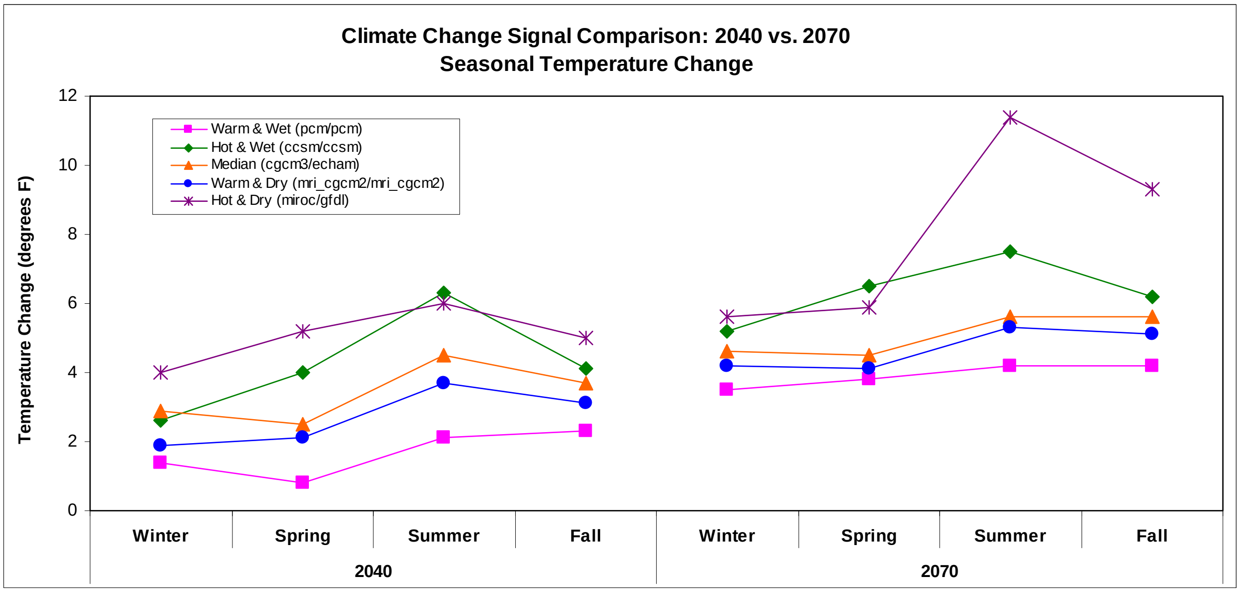


Figure 3.21 Comparison of Seasonal Temperature Change for 2040 and 2070 periods

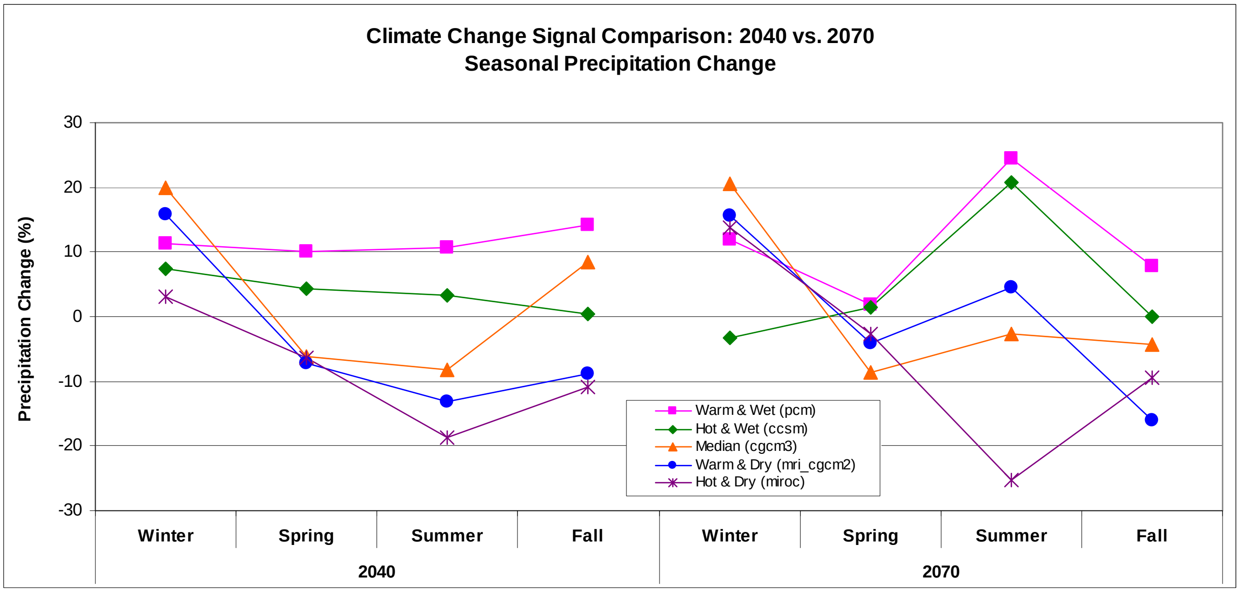


Figure 3.22 Comparison of Seasonal Precipitation Change for 2040 and 2070 periods

Hydrologic Response

The study team expected that increased warming in the 2070 period would generally lead to decreased runoff volume in the hydrologic response when compared with the 2040 period due to increases in ET. This trend was only observed in three of the five scenarios. Figure 3.23 shows the ratio of annual flow volumes between the baseline and climate adjusted flows at six selected gauges in this study, comparing the 2040 and 2070 periods. The average ratio of the six gauges is shown with a line indicating the trend from the 2040 to the 2070 period.

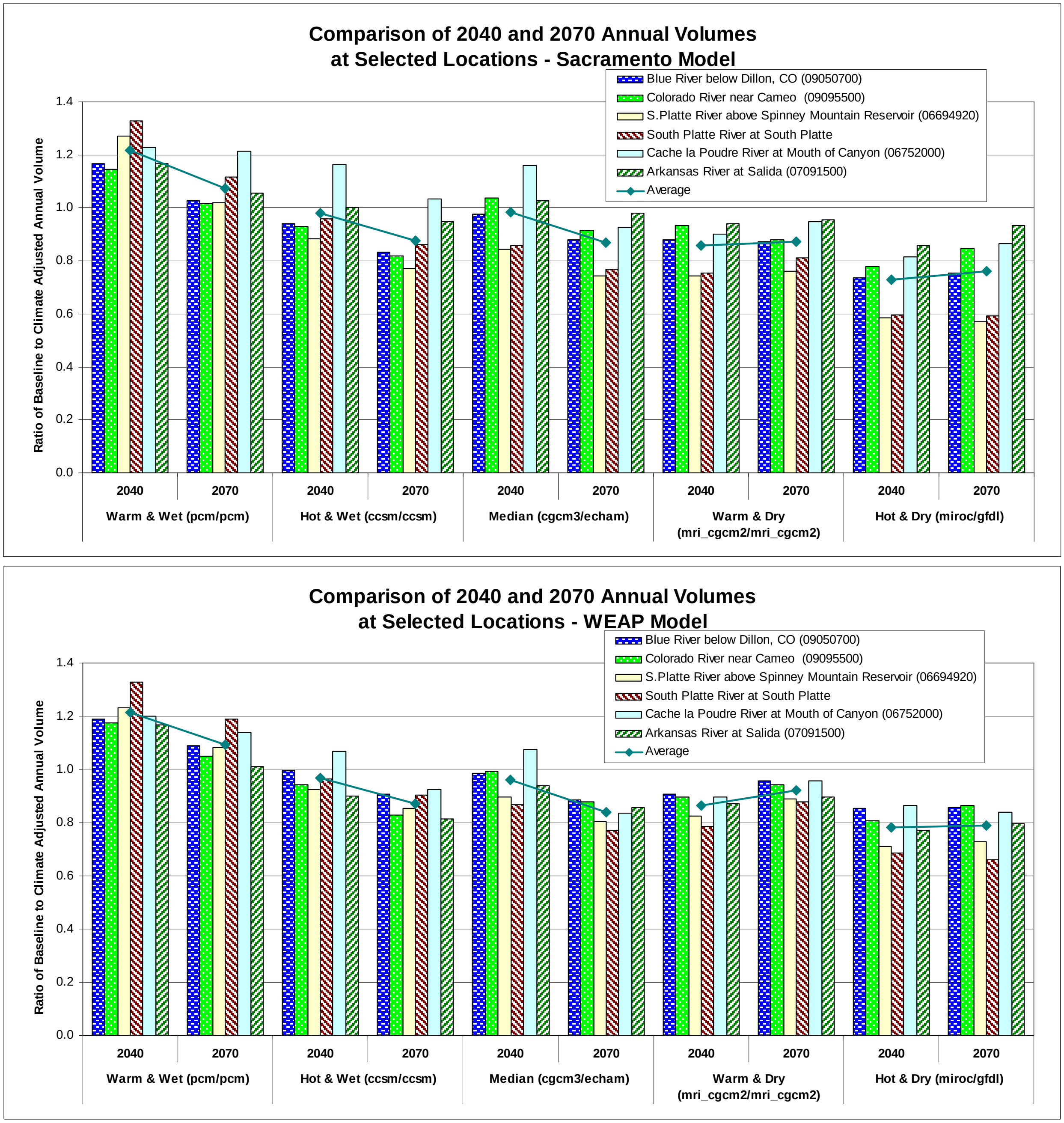


Figure 3.23 Comparison of Annual Flow Volumes at Selected Locations for 2040 and 2070 Periods

The two “dry” scenarios show an increase in annual volume from 2040 to 2070 for both the Sacramento and WEAP models. A possible explanation is that the dry models both show increased precipitation from the 2040 to the 2070 period, which may offset the temperature increase. It is also important to note that the seasonality of temperature and precipitation changes can have impacts that either exacerbate or mitigate the anticipated tendency. For example, in the 2070 hot & dry scenario the summer shows a very hot & dry condition, while the winter is relatively wet and the spring is not especially hot. It appears that this combination allows development of strong runoff in the spring and early summer with relatively moderate ET losses, while the high ET demand in the late summer encounters very little available water on which to act, effectively negating the impact of the increased temperature.

The study team anticipated increased warming from 2040 to 2070 would lead to noticeable increases in the number of days earlier that runoff would occur. Figure 3.24 shows the change in runoff timing between the baseline and climate adjusted flows at six selected gauges in this study, comparing the 2040 and 2070 periods. The average change in the number of days earlier that runoff occurs for the six locations in the graph is shown with a line indicating the trend from the 2040 to the 2070 period.

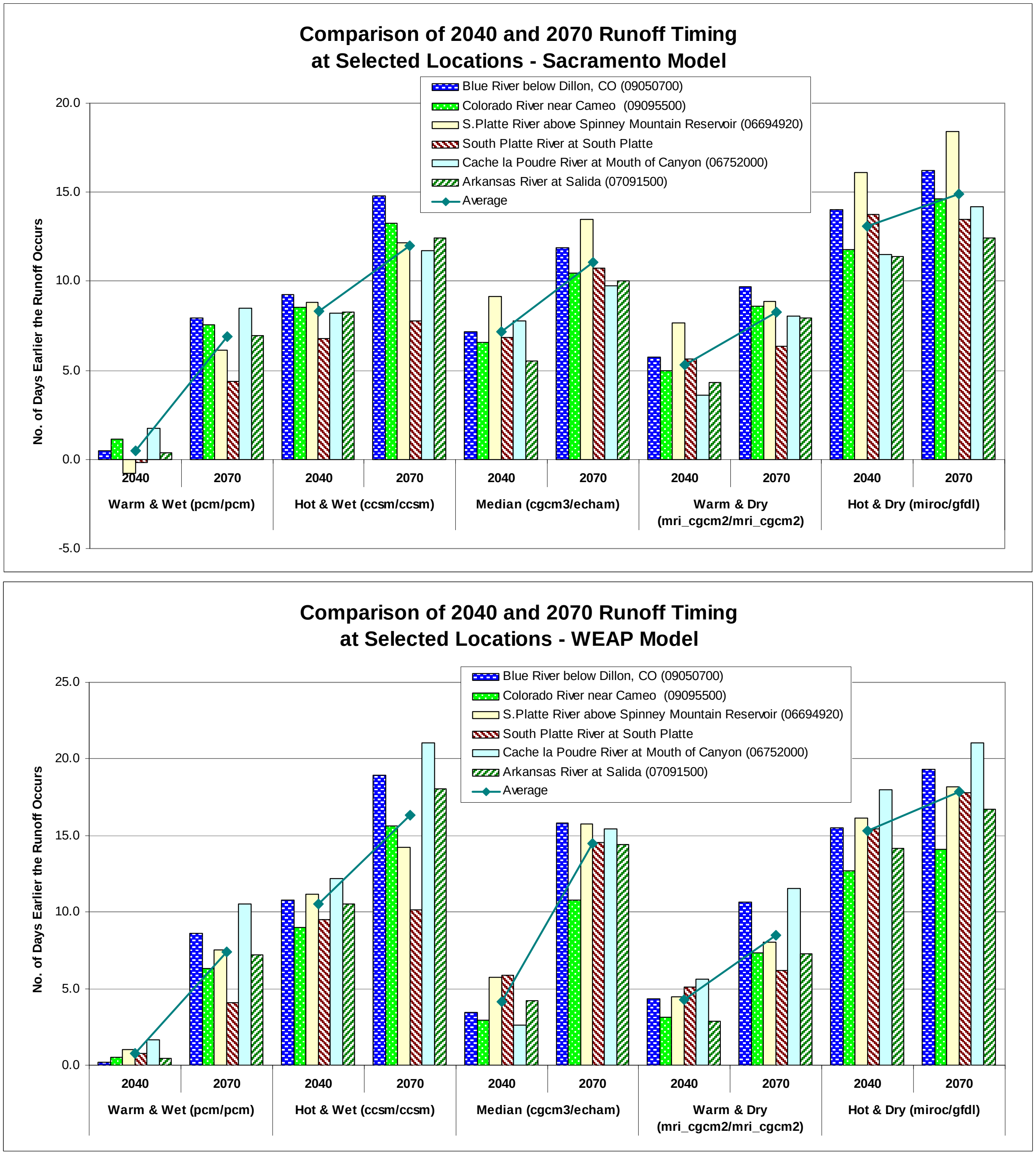


Figure 3.24 Comparison of Runoff Timing at Selected Locations for 2040 and 2070 Periods

Both the Sacramento and WEAP models show increases in the number of days earlier that runoff occurs. It is interesting to note that in the Warm & Wet scenario, both hydrologic models show an average increase from less than a day to nearly seven days earlier that runoff occurs from the 2040 to the 2070 period. This is probably due to the fact that in the 2040 period the effect of increased temperature in advancing the onset of runoff is offset by the increase in precipitation, which extends the duration of runoff, while in the 2070 period the temperature increases further while the precipitation increase remains unchanged from the 2040 level.

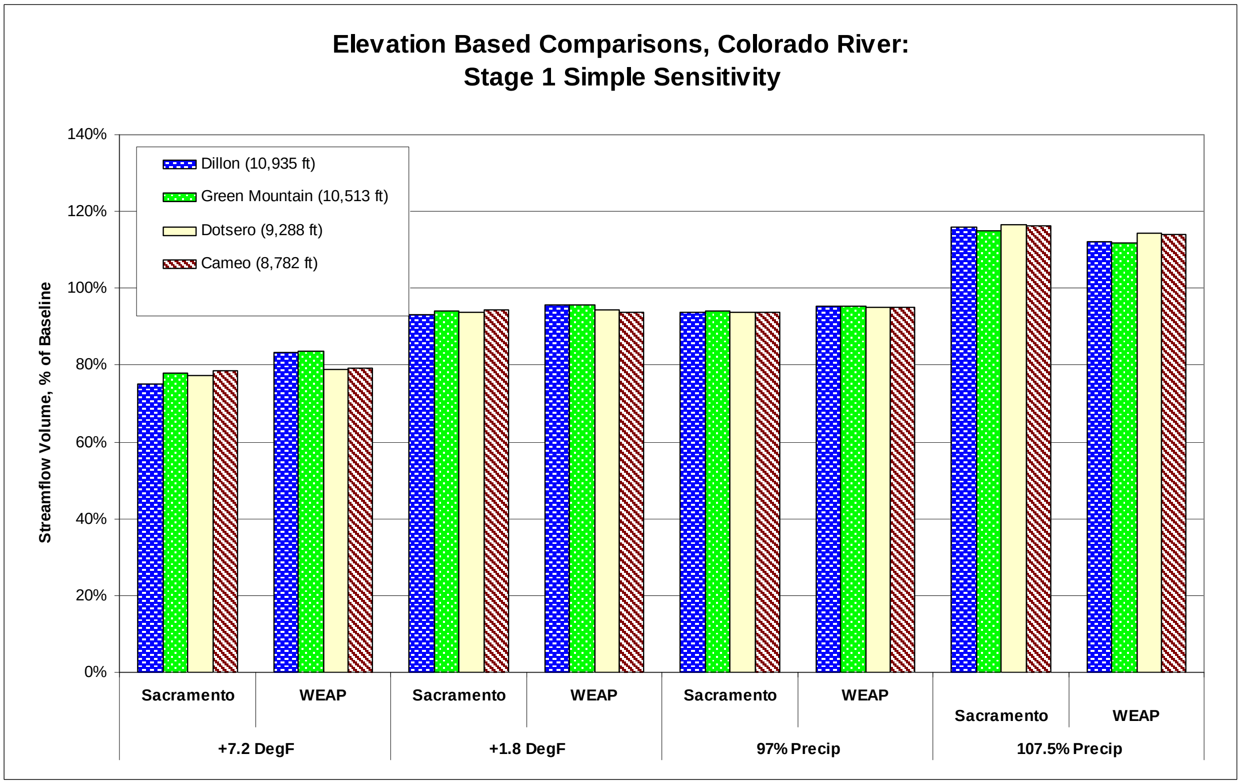
ELEVATION-BASED EVALUATION

Study participants were interested in the potential correlation that basin elevation might have on climate change impacts. Percentage changes in annual streamflow volume were reviewed for several gauge locations at different elevations in the Colorado and the South Platte basins to evaluate possible correlations. The Colorado River locations included Dillon, Green Mountain, Dotsero, and Cameo. For the South Platte River, Spinney, South Platte at South Platte, and Henderson were evaluated. Table 3.3 reports the mean basin elevation above each selected gauge location.

Table 3.3 Mean basin elevation above selected gauges

Station Location	**Elevation (ft)**
Blue River below **Dillon**, CO (09050700)	10935
Blue River below **Green Mountain** Reservoir (09057500)	10513
Colorado River near **Dotsero** (09070500)	9288
Colorado River near **Cameo** (09095500)	8782
S.Platte River above **Spinney** Mountain Reservoir (06694920)	9978
South Platte River at **South Platte**	9382
South Platte River at **Henderson** (06720500)	8322

To compare impacts for basins of different sizes and different baseline annual streamflow volumes, the average annual runoff volume for each climate scenario simulation was computed as a percent of the baseline annual volume. Figure 3.25 shows a comparison of hydrologic response to the Stage 1 simple sensitivity simulations for sub-basins in the Colorado and South Platte Rivers, organized to show sub-basins in order of decreasing elevation. Figure 3.26 shows results for the 2040 GCM-based climate simulations, and Figure 3.27 shows results for the 2070 GCM-based simulations.



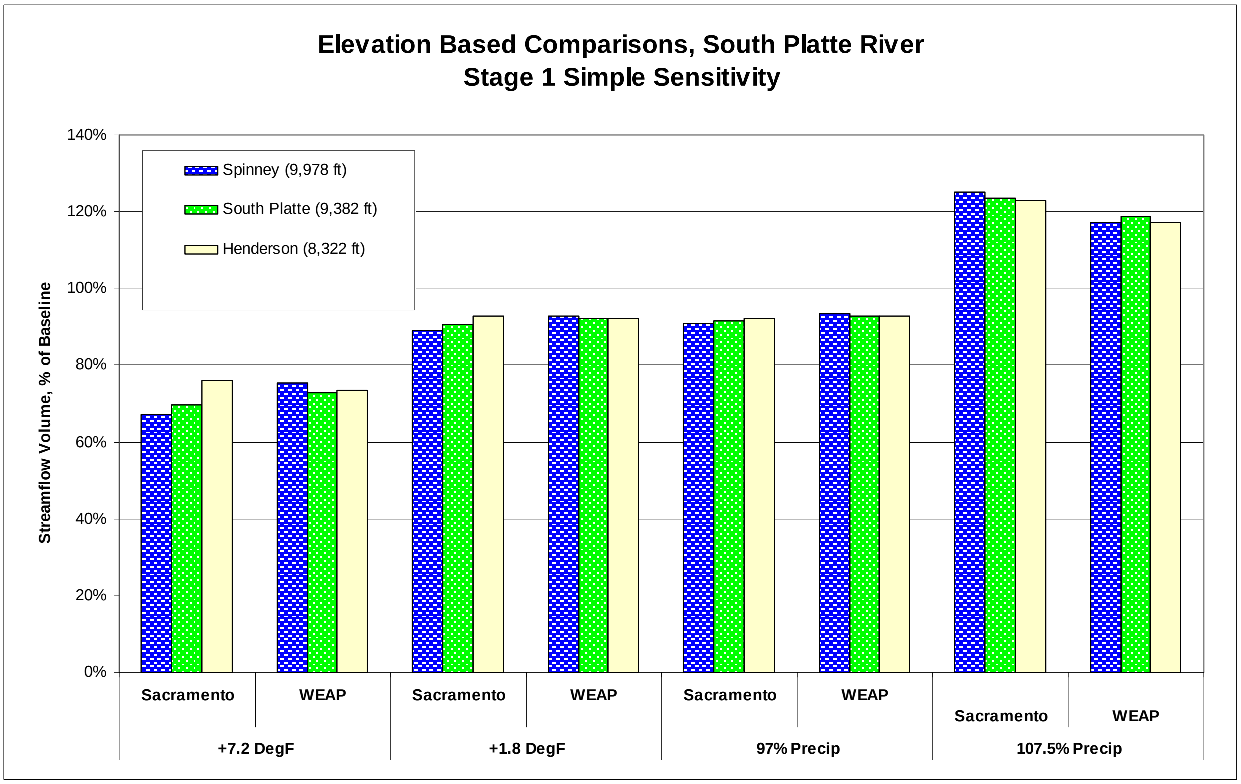


Figure 3.25 Elevation-Based Comparisons of Hydrologic Response: Stage 1 Simple Sensitivity Results for the (a) Colorado River and (b) South Platte River

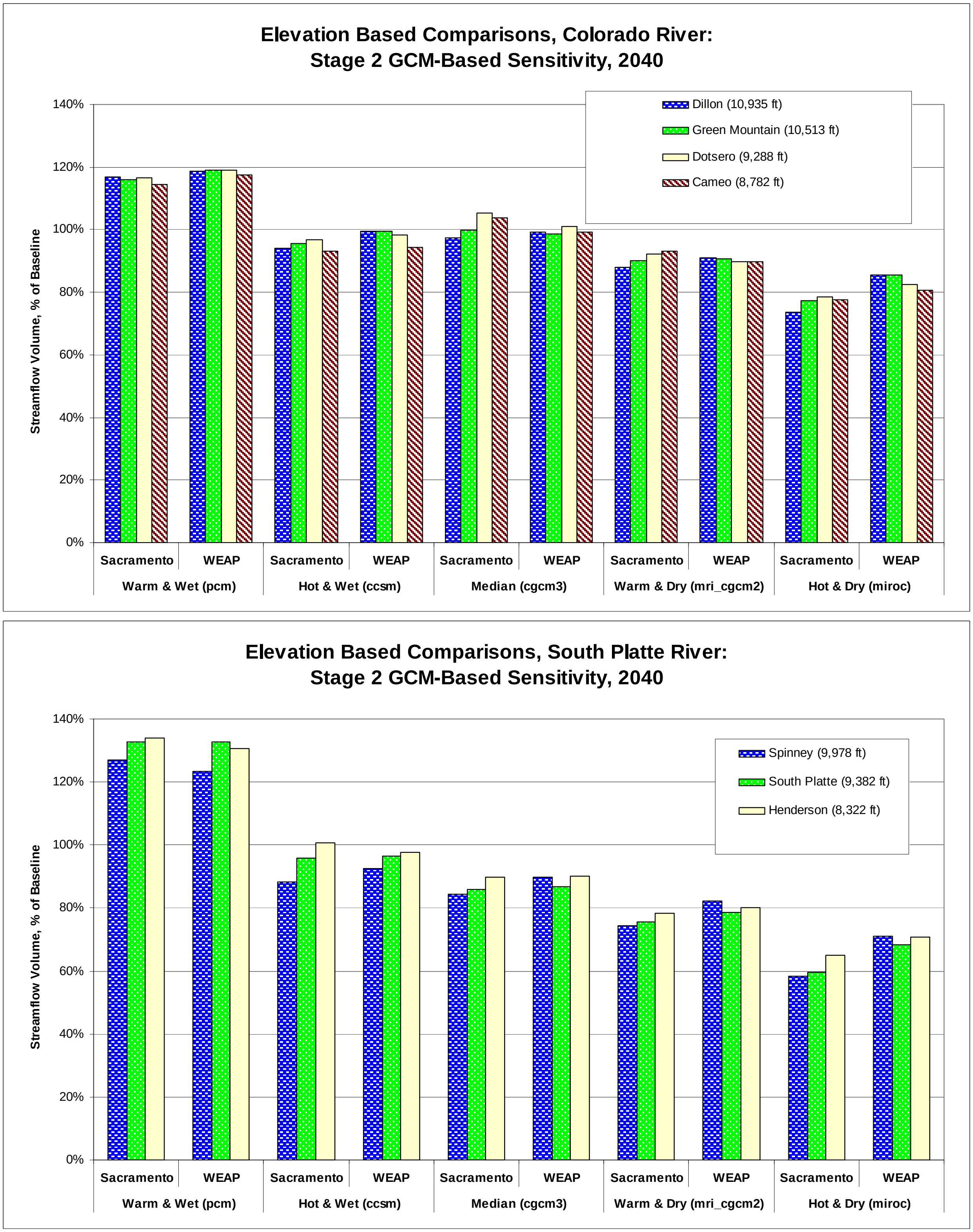


Figure 3.26 Elevation-Based Comparisons of Hydrologic Response: Stage 2 GCM-Based Sensitivity Results for 2040 for the (a) Colorado River and (b) South Platte River

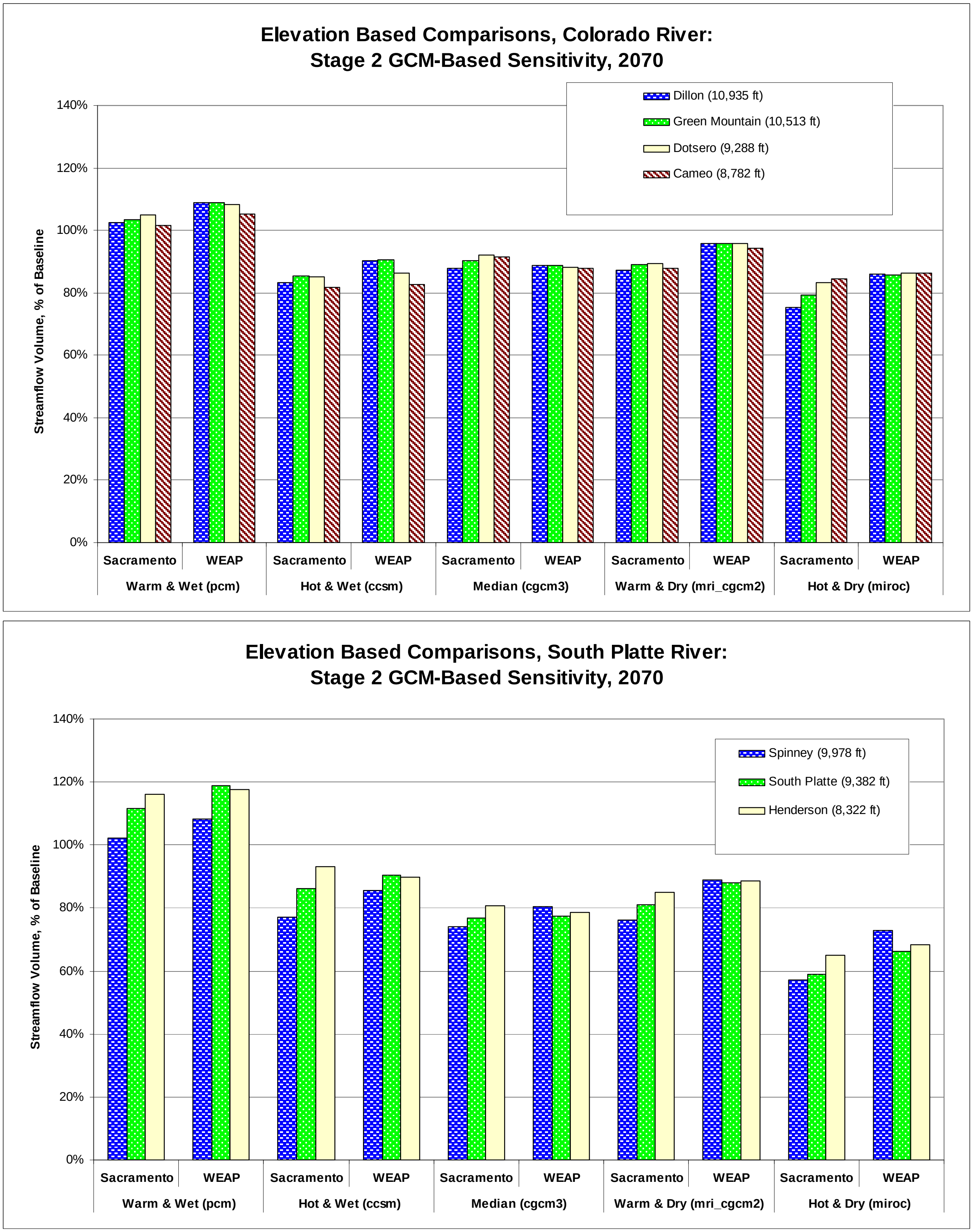


Figure 3.27 Elevation Based Comparisons of Hydrologic Response: Stage 2 GCM-Based Sensitivity Results for 2070 for the (a) Colorado River and (b) South Platte River

Several observations drawn from the figures above are listed below. :

- The WEAP model results show no discernable tendency with respect to differences in elevation.
- The Sacramento model results indicate increased sensitivity (i.e. larger reductions in streamflow) to large temperature increases at higher elevations than at lower elevations.
- The Sacramento model results indicate a weak tendency for increased sensitivity to precipitation changes at higher elevations, but only in the South Plate.
- A tendency for increased sensitivity to temperature change at higher elevations is observed in the Sacramento model results. This tendency is stronger in the South Platte than in the Colorado, and stronger in the 2070 simulations than in the 2040 simulations.

The fact that the WEAP model does not exhibit elevation-based differences in climate change impacts suggests that there are no strong elevation-based differences in the precipitation and temperature change signals computed from the GCM output (and the tendency demonstrated in the Sacramento model is based on its model formulation, and not change signals computed from the GCM output). Although this investigation used statistically downscaled data, which provided temperature and precipitation information at a resolution consistent with the scale of the hydrologic models, these data are derived from GCMs with much coarser resolution. Therefore, sub-basins in the hydrologic models that have important elevation differences might lie under just one or two grid cells in the original GCM, so that elevation-based differences in the GCM output may not be discernable.

CHAPTER 4
CONCLUSIONS

The foregoing chapters describe how this study met its primary objective of analyzing the sensitivity of streamflow to climate change for three watersheds, and developing streamflow sequences that represent the effects of climate change on the baseline streamflow. The specific study aims outlined at the end of the *Introduction – Approach* section were met by performing four tasks:

1. Selection of climate model projections - A procedure was identified and applied for selecting multiple climate model projections for use in hydrologic simulations. Ten climate scenarios were selected and associated with specific GCM projections. Characteristics of the projections were analyzed and presented. A downscaled dataset of GCM output was used in the selection and analysis procedure.
2. Historical undepleted streamflow development - A consistent sequence of historical undepleted flows for the period 1950-2005 for 18 key gauge locations were developed for use in hydrologic model calibration and also as a set of baseline flows for comparing against climate adjusted streamflow simulations.
3. Hydrologic model development - Two hydrologic models were configured and calibrated for use in computing the hydrologic response to temperature and precipitation climate changes. This included establishing climate forcing datasets of historical temperature and precipitation for input to each hydrologic model and evaluating differences in hydrologic model accuracy.
4. Assessment of streamflow sensitivity to climate change – A procedure for evaluating hydrologic response to variations in climate using uniform adjustments to temperature and precipitation was developed and tested. It was then extended to simulate the hydrologic response to possible climate change using the ten climate scenarios and associated GCM projections identified in Task 1.

The results include the documentation and evaluation of:

- Change in annual runoff volume,
- Change in the timing of runoff,
- Spatial variability associated with these changes,
- The impact as a function of basin elevation, and
- The differences between the two hydrologic models in representing the response to climate change.

The procedures used in this study and outlined in this report can be repeated for subsequent use in the region or in other parts of the country to increase understanding about climate impacts on water supplies.

FINDINGS

The pool of 112 GCMs from which 10 scenarios were selected for hydrologic simulation showed a broad range in projected future temperature and precipitation for the North-Central region of Colorado. Though all projections showed warming, the average annual temperature changes ranged from just over 1^o to nearly 6^o Fahrenheit for the 2040 time period and from about

2^o to nearly 10^o Fahrenheit for the 2040 time period. Meanwhile, average annual percent change in precipitation ranged from -15% to +17% for the 2040 time period and from -18% to +28% for the 2070 time period (See Table 2) .

Likewise, there are significant variations in hydrologic responses simulated from the selected GCM projections. For example, average annual change in streamflow volume for the South Platte below Cheesman ranges from +32% (2040 Warm & Wet scenario) to -42% (2070 Hot & Dry scenario). Analysis of the change in timing for the scenarios considered indicates that the center of mass of annual runoff arrives 1 to 14 days earlier in the 2040 simulations and 7 to 17 days earlier in the 2070 simulations.

This variability results from the differing average annual perturbations in temperature and precipitation, from the difference in the monthly distribution of those perturbations in each projection, and from differences in the spatial distribution of the changes. Those differences cannot be attributed entirely to the particular GCM model formulation, as ensembles of the same model can produce very different results. This implies that some of the variability is associated with the current state of climate science and climate modeling (Barsugli et al. 2009), even when averaged over periods of 30 years. Thus, one of the most important findings of this study is that each climate projection considered has a unique impact on runoff volume, and to grasp the broad picture of future possible changes in streamflow, the range of impacts from multiple scenarios needs to be considered, as opposed to looking for a central tendency or averages of simulation results. This application of a scenario approach also helps to inform climate impact assessment and response for individual water managers and utilities by emphasizing variability, while noting that no single projection is the most likely (for more information on scenarios and scenario planning see "The Art of the Long View," by Peter Schwartz [1991]). Within this context, the following are key observations drawn from this study.

- GCM model output encompasses a broad range of projected changes to future temperature and precipitation.
- There is substantial variability in projected future streamflow based on the range of climate model projections used for streamflow simulation.
- Although the results indicate both increases and decreases in annual streamflow volume, depending on the projection used, more of the selected climate projections resulted in decreases than increases.
- Where decreased annual streamflow volume is indicated for a given projection, it is a result of the computed increase in ET due to increased temperatures, coupled with either a decrease in precipitation or else a small increase in precipitation insufficient to offset the increased temperature effect.
- Where increased annual streamflow volume is indicated for a given projection, it is a result of increased precipitation sufficient to offset the increased temperature effect for that projection.
- The average annual characteristics of climate models over a large area (e.g. average annual precipitation and temperature change) are not the only predictors of streamflow response to a given projection. The spatial and temporal distribution of those changes across multiple sub-basins and over the twelve-month period has considerable influence on hydrologic model results.
- The GCM outputs include important patterns of spatial variability that differ between projections and produce distinct hydrologic responses among sub-basins. For

example, a GCM projection showing, on an average, an increase in precipitation over the study area is likely to have some areas of significant precipitation increase coupled with areas of modest decrease, with corresponding variation in the hydrologic response of the sub-basins in those two areas.

- GCM temperature and precipitation perturbations are not uniform over the course of the year but vary by month, and differ between projections. The temporal distribution of these changes is important because an increase in temperature can have a different impact in the late summer, when soil moisture is limited, versus early spring when the melting snowpack results in increased availability of surface water and soil moisture. Likewise, precipitation changes appear to have more impact under saturated soil conditions in the spring than under dry conditions in the summer and fall months.
- The hydrologic models responded similarly to fixed perturbations of climate inputs applied in the simple sensitivity assessment.
- While differences exist between the two hydrologic models in simulating specific river basins or in response to specific GCM projections, the models are in agreement about the general tendency for each projection and within each river basin.
- Although *potential* ET might be greater due to warming, it does not necessarily mean that *actual* ET will increase accordingly, as reduced precipitation may lead to limited soil moisture or as earlier runoff may lead to reduced late summer soil moisture (these factors are explicitly addressed in the methodology of this study).
- Simulated runoff timing is determined by complex factors that differ between models, but notwithstanding those differences, the results show relatively close agreement between models in projecting changes in runoff timing.
- At the scale of the river basins evaluated in this study, there does not appear to be a consistent tendency among GCMs regarding elevation-based differences in climate change patterns. Similarly, there are no clear tendencies regarding elevation-based differences in simulated hydrologic response that are evident from the results of both hydrologic models for multiple river basins.
- While increased temperatures are shown to reduce simulated average annual streamflow, the reductions are not uniform across the study area, with the driest basins, such as those in the South Platte, experiencing the greatest percent reduction in streamflow due to warmer conditions, while the wetter basins, including the upper areas of the Colorado, show a smaller percent reduction.

STRENGTHS AND LIMITATIONS IN APPLYING THE STUDY APPROACH

One of the strengths of the overall approach employed in this study is that it allowed the spatially and temporally variable climate change signal to be incorporated into the hydrologic simulation while preserving the spatial and temporal structure and variability of the historical climate. By selecting specific GCM projections to represent the climate change signal on an average monthly basis instead of using average annual temperature and precipitation adjustments, the results of this study highlight the variability that can result from particular combinations of monthly distributions of temperature and precipitation change. Another benefit of the approach is that it produces output time series representing possible future scenarios under climate change that can be applied to existing simulation tools used by water managers and utilities for comparison with simulations based on historical time series that do not consider climate change. The approach could also be expanded without much difficulty to include all of the available 112 GCM projections (as well as projections that might be developed in the future) for a more complete analysis.

The following are limitations in the application of the study approach that became apparent over the course of the investigation:

- In selecting a specific GCM projection to represent a particular region of the climate change space, the peculiarities of that projection add to the variability in the results and do not permit an evaluation of trend associated with that space. One way to overcome this deficiency without losing the benefit noted above would be to simply use all of the GCM projections as input to a hydrologic model and then evaluate the hydrologic outputs from all 112 projections to identify trends.
- The study approach does not provide any insight into the potential for increased or decreased intensities of rainfall outside of the average monthly change, or for variation in the diurnal distribution of temperature increases, or any other characteristic of the GCMs that may indicate fundamental changes in climatic characteristics beyond the average monthly change in temperature and precipitation. This was not a serious limitation for the purposes of this study, but might be important in areas where changes in peak flows are of greater interest. Any efforts to overcome this particular limitation would have to overcome the lack of GCM output available in a format that would support more detailed analysis and would have to be justified with confidence that the climate models are in fact capable of representing those changes in a meaningful way.
- While the response of evapotranspiration (ET) to temperature change is a key element in determining changes in runoff volume, there are additional variables beyond temperature that influence ET that were not part of the downscaled GCM outputs and could not be incorporated into the study approach.
- The study approach targets evaluations for specific future points in time, without representing the gradual change in climate and associated runoff that may occur over time. This permits managers to plan for a specific future point in time, but does not facilitate evaluating the impact of climate change on vulnerability of water supplies during the period leading up to a future system design or state.

LESSONS LEARNED

Two primary considerations in assessing future water availability for Front Range water providers are average annual volume and the timing of runoff. Because the water supply for these agencies is primarily stored in the snowpack, permanent changes in the timing and volume of this important resource would have major impacts on water availability and would force changes in water management strategies. The change in annual runoff volume and timing of runoff, together with the potential range of these changes, are the outputs of the study that are of greatest interest to the participants and their constituents. These two outputs are tied to a few fundamental processes represented in the two hydrologic models. These include, among others, snow accumulation and melt processes, the phase in which precipitation occurs (rain or snow), movement and storage of water through soil layers, and ET from the surface and subsurface soil. The most important inputs that govern these processes are temperature and precipitation.

GCM output includes projections of future temperature and precipitation that can be used in conjunction with hydrologic models to estimate changes in volume and timing of runoff. Output from currently available models projects temperature and precipitation changes within a wide range. The variety in GCM output results in a wide range of estimates of change in runoff volume and timing.

Runoff timing is most sensitive to temperature, due to its effect on the form of precipitation (rain or snow) and on snowmelt. Precipitation changes alone have a minor influence on runoff timing. Even changes in the timing of precipitation have little impact on runoff timing because of the dominance of snowmelt in the annual runoff cycle and the controlling impact of temperature on snowmelt. Because all of the climate scenarios indicate increased temperature, nearly all of the scenarios simulated indicate earlier runoff, with the effect being more pronounced in the 2070 period. While the range of projections regarding the number of days earlier that runoff will occur is broad, the tendency to earlier runoff is uniform.

Simulated runoff volume is sensitive to both precipitation and temperature change. The sensitivity to temperature change is because of the influence of temperature on ET in the hydrologic model formulations. Because all of the climate scenarios indicate increased temperature, all of the climate-adjusted runoff simulations are impacted by an increase in ET and a corresponding reduction in volume. Many of the climate projections show a slight increase in precipitation, which partially or wholly offsets the reduction in runoff caused by increased ET. Those projections that show reduction in precipitation accentuate the reduced runoff volume that results from increased temperature. The occurrence of both increases and decreases in precipitation accentuate the spread of volume changes simulated from the selected climate scenarios.

Based on these observations, study participants may wish to prepare for the impacts of climate change on water availability, with the following considerations:

- Expect runoff to occur earlier.
- Consider contingency plans for both increases and decreases in average annual runoff.
- Monitor evolving indicators of climate change at both global and regional scales to identify trends and evaluate the relative merits of existing and future climate models..
- Broaden the scope of selected climate models to use in hydrologic simulation to more fully explore the range and distribution of possible outcomes.
- Be prepared to incorporate updated climate model outputs in planning processes based on forthcoming advances in climate science.
- Encourage advances in climate science that will facilitate accurate hydrologic assessment.

Climate change adaptation is about preparing for change and variability in the future. This study provides important information to water utilities and managers to aid in identifying the hydrologic response to possible climate change. The following expands on the ideas noted above for application of the results of the study and recommendations for future investigation and research.

CHAPTER 5
APPLICATION AND RECOMMENDATIONS

APPLICATIONS FOR WATER PROVIDERS

The results of this study can be applied at multiple levels, from the perspective of the specific study participants that use the outputs directly, to readers who may be interested in climate change impacts in Colorado, to others who may be interested in applying the methodology of this study to other regions. One of the important outputs of this study is a set of climate-adjusted streamflow sequences representing the impact of selected future climate projections on undepleted streamflow volume for 18 gauge locations. Regional water providers in Colorado can use these climate-adjusted streamflow sequences in conjunction with water system models to estimate the impacts of climate change for future water supply planning purposes. Water providers can use this information in their planning to identify robust strategies for water management decisions that respond to variability and uncertainty in annual water supplies.

The methodology of GCM selection, development of adjusted historical climate sequences, and hydrologic simulation that was developed in this study can be applied widely to assess climate impacts on water supplies both for additional projections in the basins studied or for other locations where there is access to downscaled GCM datasets. Although applying this methodology does not require a thorough understanding of climate science, users of the methodology should be informed about the capabilities and limitations of climate science and models. An important application note is that because of the uncertainty and variability in all of the characteristics of climate models that ultimately impact the timing and volume of runoff, it may be valuable and important to simulate water systems operations using multiple climate projections to reveal potential vulnerabilities specific to the hydrologic response to each projection.

Finally, it is important for the water utility community to communicate its needs regarding developments in climate science and required outputs from the models to the climate research community so that subsequent efforts might emerge as helpful in modeling hydrologic impacts of climate change.

RECOMMENDATIONS FOR ADDITIONAL INVESTIGATION AND RESEARCH

The findings and lessons learned from this study indicate opportunities to improve understanding of the issues surrounding hydrologic response to climate change. To provide better information for planning, additional investigation efforts should seek to better understand the factors that contribute to climate variability while refining aspects of the procedure that can help to reduce uncertainty. The brief available historic record reflects basic inter-annual variability and some, but not all of the long-term variability in the natural climate system. Climate models attempt to represent variations that may result from increased emissions. Both are important for understanding potential impacts on water supplies in the future. Uncertainty results from lack of knowledge or understanding, either on the part of the science community or within the formulations of climate and hydrologic models. Some uncertainty can be reduced, for example through improved models, but some cannot, including the uncertainty associated with the chaotic component of climate and weather systems. The following specific suggestions for additional investigation and research respond to the foregoing suggestions.

1. Climate Model Investigation and development – Output from climate models formed the basis for the evaluation of changes in runoff volume and timing in this study. Several suggestions for research and development relate to climate modeling.
    - It has been noted that precipitation is both a hydrologic model input to which runoff volume is highly sensitive, as well as a widely varying climate model output, including projections of both increase and decrease. This is an important source of uncertainty in the runoff simulation results. In the short term, it would be helpful to develop a better understanding of the nature of precipitation projections in climate-change modeling, including the degree of confidence that might be lent to them, and potential differences between models in accurately simulating precipitation trends.
    - Investigate and apply possible methods to extract information from the climate models about changes in inter-annual and daily climate characteristics. For example, droughts and floods will be impacted by changing durations of high temperatures or low precipitation, or by increases or decreases in precipitation intensity. No information of this nature can be inferred from the models using the data and methods of this study. An investigation of this nature should be accompanied or preceded by an investigation of the expected skill of climate models in predicting changes in these climate characteristics as a function of the climate model inputs.
2. Additional Scenarios – This study considered just five scenarios from a dataset of 112 possible projections for analysis for each of two future periods. Using the methods and procedures developed for this study, a subsequent analysis based on a simulation of *all* of the available GCM projections would be instructive in better understanding the distribution of variability among the streamflow responses to the GCMs.
3. Demand – In using the results of this study in water system models, methods and procedures could be formulated and applied to simulate the impact to corresponding climate change scenarios on demand.
4. Planning strategies – Many of the participating water agencies formulate their planning problems within the context of the historical hydrology, as their models rely on these data, and not on the explicit use of climate variables like precipitation, temperature, etc. The approach used in this study allows direct comparisons of volume and even direct simulation of water system models using climate-adjusted runoff volumes. It may be instructive, however, to identify new strategies for planning that would facilitate the direct use of climate-change time series, so that system models can be more forward looking, indicating the development of climate change impacts over time.
5. Evapotranspiration – A major factor in projecting reduced average annual streamflow volumes in this study is the simulation of increased ET resulting from warmer temperatures. ET is computed in both hydrologic models as a function of soil-water availability and PET. PET is computed for each basin with temperature as the only climate variable in the Penman Monteith equation, yet there are other variables in the PET formulation that could change under future warming, including solar radiation, wind speed, and relative humidity. Currently there are no simple ways to extract information about these variables from climate models for use in hydrologic simulation, nor is it clear to what degree climate models can accurately represent changes in these variables under the influence of climate change. The following suggestions may assist in improving

estimates of ET in response to climate change and in improving confidence in those estimates:

- Work with climate model experts to identify elements of climate models that correspond with variables that impact ET, evaluate climate-model skill in predicting these variables, and determine feasibility of extracting the information from climate models and including them in the hydrologic modeling procedure.
- Incorporate a daily ET computation component into the SAC model and evaluate the correlation between temperature and ET surrogates (runoff). A heuristic adjustment factor could also be included as a calibration parameter to either amplify or dampen the sensitivity of potential ET to temperature change, which was computed using the Penman-Monteith formulation. This approach could help assess the effectiveness of the models in historical dry and wet periods (or warm and cool periods) to increase confidence that the effect of climate changed inputs can be properly represented in the outputs.

Many of the participants in this study began with limited experience and knowledge in climate science and climate modeling, or of how climate model outputs might be applied to hydrologic models, to gain insight into changes in runoff volume and timing under the influence of climate change. Participation in this study has both broadened and deepened the understanding of the participants, and the study methodologies are developed sufficiently such that many of the suggestions for additional investigation and research noted above should now be more accessible to the participants.

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ABBREVIATIONS

AET	actual evapotranspiration
AOP	annual operating plans
ARBFC	Arkansas-Red Basin River Forecast Center
CBRFC	Colorado Basin River Forecast Center
CDSS	Colorado Decision Support System
CMIP3	Coupled Model Intercomparison Project phase 3
° C	degrees Celsius
CWCB	Colorado Water Conservation Board
DSS	decision support system
ET	evapotranspiration
° F	degrees Fahrenheit
GCM	general circulation models
IPCC	Intergovernmental Panel on Climate Change
MAP	Mean Areal Participation
MAT	Mean Areal Temperature
MBRFC	Missouri Basin River Forecast Center
NCAR	National Center for Atmospheric Research
NSE	Nash Sutcliffe Efficiency
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
PCM	Parallel Climate Model
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PET	Potential Evapotranspiration
RMSE	root mean square error
SAC-SMA	Sacramento Soil Moisture Accounting model
SRES	Special Report on Emissions Scenarios
WEAP	Water Evaluation and Planning
WGCM	Working Group on Coupled Modeling
WCRP	World Climate Research Programme
WWA	Western Water Assessment

APPENDIX A: CALIBRATION STATISTICS

SACRAMENTO MODEL CALIBRATION STATISTICS

Sacramento	Overall	Wet Years							Normal Years							Dry Years						
Watershed	Nash Sutcliffe Efficiency	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE
Colorado River		(TAF)	(TAF)			(TAF)	(TAF)	(TAF)	(TAF)	(TAF)			(TAF)	(TAF)	(TAF)	(TAF)	(TAF)			(TAF)	(TAF)	(TAF)
Fraser River at Granby (09034000)	0.940	218	214	-2%	0.960	18	24	5	147	155	5%	0.920	12	16	4	94	96	1%	0.865	8	9	3
Williams Fork near Leal (09035700)	0.915	103	99	-4%	0.934	9	12	3	74	72	-3%	0.891	6	9	3	52	51	-1%	0.917	4	5	2
Blue River below Green Mountain Reservoir (09057500)	0.950	522	540	3%	0.944	44	54	13	375	372	-1%	0.953	31	38	8	265	265	0%	0.935	22	22	6
Blue River below Dillon, CO (09050700)	0.945	306	314	3%	0.945	25	33	8	217	218	0%	0.945	18	22	5	148	144	-3%	0.921	12	13	4
Colorado River near Granby, CO (09019500)	0.936	365	392	8%	0.940	30	45	11	267	265	-1%	0.928	22	33	9	185	174	-5%	0.940	15	21	5
Colorado River near Dotsero (09070500)	0.944	2,773	2,867	3%	0.955	231	289	61	1,973	1,977	0%	0.932	164	198	52	1,346	1,365	1%	0.915	112	120	35
Colorado River near Cameo (09095500)	0.955	4,839	4,994	3%	0.964	403	485	93	3,362	3,396	1%	0.943	280	325	77	2,310	2,350	2%	0.935	193	189	48
Homestake Creek at Gold Park (09064000)	0.937	60	61	1%	0.932	5	8	2	42	42	-1%	0.941	4	6	1	29	30	5%	0.930	2	4	1
Roaring Fork River near Aspen (09073400)	0.946	146	149	2%	0.934	12	18	5	105	106	0%	0.957	9	13	3	78	78	-1%	0.943	7	9	2
South Platte																						
S.Platte River above Spinney Mountain Reservoir (06694920)	0.762	122	126	3%	0.760	10	12	6	74	76	3%	0.731	6	7	3	42	51	22%	0.577	3	4	2
South Platte River below Cheesman Reservoir	0.798	258	243	-6%	0.798	21	24	11	138	138	0%	0.759	11	11	5	76	96	26%	0.453	6	6	5
South Platte River at South Platte	0.844	464	425	-8%	0.874	39	42	15	249	259	4%	0.725	21	18	10	146	180	24%	0.580	12	11	7
South Platte River at Henderson (06720500)	0.850	877	794	-9%	0.856	73	75	29	461	480	4%	0.759	38	31	15	261	331	27%	0.538	22	17	11
South Platte Tributaries																						
Cache la Poudre River at Mouth of Canyon (06752000)	0.901	406	369	-9%	0.906	34	52	16	270	249	-8%	0.892	22	32	10	165	168	2%	0.854	14	18	7
St. Vrain Creek at Canyon Mouth near Lyons	0.903	164	159	-3%	0.892	14	18	6	113	113	1%	0.919	9	12	3	72	75	5%	0.841	6	8	3
Big Thompson River at Mouth of Canyon near Drake (06738000)	0.907	176	165	-6%	0.921	15	20	5	119	123	3%	0.896	10	12	4	80	81	1%	0.813	7	8	3
Boulder Creek at Orodell	0.887	96	91	-5%	0.912	8	10	3	71	72	1%	0.886	6	8	3	48	49	4%	0.733	4	5	2
Arkansas River																						
Arkansas River at Salida (07091500)	0.818	577	547	-5%	0.838	48	55	22	402	386	-4%	0.808	33	32	14	292	321	10%	0.595	24	20	13

WEAP MODEL CALIBRATION STATISTICS

WEAP	Overall	Wet Years							Normal Years							Dry Years						
Watershed	Nash Sutcliffe Efficiency	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE	Historical Annual Mean	Baseline Annual Mean	Annual Bias	Nash Sutcliffe Efficiency	Historical Monthly Mean	Standard Deviation	RMSE
Colorado River		(TAF)	(TAF)			(TAF)	(TAF)	(TAF)	(TAF)	(TAF)			(TAF)	(TAF)	(TAF)	(TAF)	(TAF)			(TAF)	(TAF)	(TAF)
Fraser River at Granby (09034000)	0.690	218	191	-13%	0.760	18	25	12	147	157	6%	0.602	12	16	10	94	102	8%	0.480	8	10	6
Williams Fork near Leal (09035700)	0.746	103	85	-17%	0.791	9	13	6	74	76	3%	0.766	6	9	4	52	58	11%	0.303	4	6	4
Blue River below Green Mountain Reservoir (09057500)	0.781	522	476	-9%	0.802	44	55	24	375	351	-6%	0.765	31	38	18	265	255	-4%	0.631	22	24	13
Blue River below Dillon, CO (09050700)	0.777	306	299	-2%	0.801	25	34	15	217	216	0%	0.755	18	22	11	148	155	5%	0.635	12	14	8
Colorado River near Granby, CO (09019500)	0.714	365	328	-10%	0.834	30	46	18	267	252	-6%	0.615	22	33	21	185	164	-11%	0.586	15	22	14
Colorado River near Dotsero (09070500)	0.790	2,773	2,903	5%	0.797	231	296	130	1,973	2,058	4%	0.778	164	198	93	1,346	1,357	1%	0.715	112	132	64
Colorado River near Cameo (09095500)	0.793	4,839	4,784	-1%	0.817	403	498	207	3,362	3,384	1%	0.779	280	325	153	2,310	2,291	-1%	0.592	193	212	120
Homestake Creek at Gold Park (09064000)	0.738	60	56	-6%	0.756	5	8	4	42	39	-8%	0.730	4	6	3	29	26	-8%	0.641	2	4	2
Roaring Fork River near Aspen (09073400)	0.630	146	132	-9%	0.734	12	18	9	105	118	12%	0.506	9	13	9	78	81	4%	0.621	7	9	5
South Platte																						
S.Platte River above Spinney Mountain Reservoir (06694920)	0.669	122	98	-20%	0.634	10	13	7	74	62	-16%	0.648	6	7	4	42	47	14%	0.607	3	5	2
South Platte River below Cheesman Reservoir	0.736	258	219	-15%	0.712	21	26	13	138	136	-1%	0.684	11	11	6	76	99	29%	0.630	6	9	4
South Platte River at South Platte	0.731	464	382	-18%	0.689	39	44	23	249	241	-3%	0.694	21	19	10	146	162	11%	0.690	12	15	6
South Platte River at Henderson (06720500)	0.711	877	720	-18%	0.680	73	81	43	461	456	-1%	0.597	38	31	19	261	309	18%	0.607	22	27	11
South Platte Tributaries																						
Cache la Poudre River at Mouth of Canyon (06752000)	0.612	406	371	-9%	0.628	34	53	31	270	275	2%	0.638	22	32	19	165	192	17%	0.074	14	20	17
St. Vrain Creek at Canyon Mouth near Lyons	0.677	164	145	-12%	0.699	14	19	10	113	103	-9%	0.622	9	12	7	72	80	11%	0.638	6	8	5
Big Thompson River at Mouth of Canyon near Drake (06738000)	0.594	176	173	-1%	0.582	15	20	13	119	114	-4%	0.563	10	12	8	80	79	-2%	0.600	7	8	5
Boulder Creek at Orodell	0.758	96	87	-9%	0.771	8	11	5	71	68	-4%	0.763	6	8	4	48	50	6%	0.582	4	5	3
Arkansas River																						
Arkansas River at Salida (07091500)	0.721	577	528	-8%	0.756	48	56	27	402	406	1%	0.664	33	32	18	292	320	10%	0.530	24	23	14

APPENDIX B: ANNUAL PERCENT CHANGE IN STREAMFLOW VOLUME

SACRAMENTO MODEL ANNUAL PERCENTAGE CHANGES BY SCENARIO

Sacramento	Simple Assessment							2040						2070		
Watershed	Percent Change from Model Baseline						Percent Change from Model Baseline						Percent Change from Model Baseline			
Colorado River	+7.2 DegF	+1.8 DegF	97% Precip	107.5% Precip		Warm & Wet (pcm)	Hot & Wet (ccsm)	Median (cgcm3)	Warm & Dry (mri_cgcm2)	Hot & Dry (miroc)		Warm & Wet (pcm)	Hot & Wet (ccsm)	Median (echam)	Warm & Dry (mri_cgcm2)	Hot & Dry (gfdl)
Fraser River at Granby (09034000)	-24%	-6%	-6%	17%		19%	1%	5%	-9%	-22%		8%	-12%	-8%	-9%	-19%
Williams Fork near Leal (09035700)	-20%	-5%	-6%	15%		16%	-2%	1%	-10%	-22%		6%	-11%	-8%	-9%	-20%
Blue River below Green Mountain Reservoir (09057500)	-22%	-6%	-6%	15%		16%	-5%	0%	-10%	-23%		3%	-15%	-10%	-11%	-21%
Blue River below Dillon, CO (09050700)	-25%	-7%	-6%	16%		17%	-6%	-2%	-12%	-26%		3%	-17%	-12%	-13%	-25%
Colorado River near Granby, CO (09019500)	-24%	-7%	-6%	16%		16%	2%	7%	-9%	-21%		11%	-9%	-8%	-8%	-19%
Colorado River near Dotsero (09070500)	-23%	-6%	-6%	16%		16%	-3%	5%	-8%	-21%		5%	-15%	-8%	-11%	-17%
Colorado River near Cameo (09095500)	-21%	-6%	-6%	16%		15%	-7%	4%	-7%	-22%		1%	-18%	-8%	-12%	-15%
Homestake Creek at Gold Park (09064000)	-13%	-4%	-5%	13%		13%	-6%	1%	-6%	-18%		1%	-14%	-6%	-10%	-14%
Roaring Fork River near Aspen (09073400)	-19%	-6%	-6%	13%		9%	-13%	-4%	-10%	-24%		-6%	-22%	-12%	-15%	-18%
South Platte																
S.Platte River above Spinney Mountain Reservoir (06694920)	-33%	-11%	-9%	25%		27%	-12%	-16%	-26%	-42%		2%	-23%	-26%	-24%	-43%
South Platte River below Cheesman Reservoir	-32%	-10%	-9%	25%		32%	-8%	-15%	-25%	-42%		8%	-18%	-25%	-21%	-42%
South Platte River at South Platte	-30%	-9%	-9%	24%		33%	-4%	-14%	-24%	-40%		12%	-14%	-23%	-19%	-41%
South Platte River at Henderson (06720500)	-25%	-7%	-8%	22%		34%	0%	-10%	-22%	-36%		16%	-8%	-20%	-16%	-36%
South Platte Tributaries																
Cache la Poudre River at Mouth of Canyon (06752000)	-22%	-7%	-7%	19%		23%	16%	16%	-10%	-18%		21%	3%	-7%	-5%	-14%
St. Vrain Creek at Canyon Mouth near Lyons	-16%	-5%	-6%	16%		20%	7%	4%	-11%	-20%		16%	0%	-8%	-6%	-19%
Big Thompson River at Mouth of Canyon near Drake (06738000)	-21%	-6%	-6%	17%		21%	9%	7%	-10%	-20%		17%	-1%	-9%	-7%	-17%
Boulder Creek at Orodell	-18%	-5%	-6%	15%		18%	3%	-1%	-12%	-20%		12%	-4%	-10%	-8%	-22%
Arkansas River																
Arkansas River at Salida (07091500)	-6%	-3%	-7%	14%		16%	-1%	2%	-7%	-15%		5%	-6%	-3%	-6%	-8%

WEAP MODEL ANNUAL PERCENTAGE CHANGES BY SCENARIO

WEAP	Simple Assessment						2040					2070		
Watershed	Percent Change from Model Baseline					Percent Change from Model Baseline					Percent Change from Model Baseline			
Colorado River	+7.2 DegF	+1.8 DegF	97% Precip	107.5% Precip	Warm & Wet (pcm)	Hot & Wet (ccsm)	Median (cgcm3)	Warm & Dry (mri_cgcm2)	Hot & Dry (miroc)	Warm & Wet (pcm)	Hot & Wet (ccsm)	Median (echam)	Warm & Dry (mri_cgcm2)	Hot & Dry (gfdl)
Fraser River at Granby (09034000)	-23%	-6%	-5%	14%	21%	2%	0%	-11%	-17%	12%	-10%	-15%	-6%	-19%
Williams Fork near Leal (09035700)	-8%	-2%	-4%	9%	15%	4%	3%	-5%	-9%	11%	-1%	-4%	1%	-8%
Blue River below Green Mountain Reservoir (09057500)	-17%	-4%	-5%	12%	19%	-1%	-1%	-9%	-15%	9%	-10%	-11%	-4%	-14%
Blue River below Dillon, CO (09050700)	-16%	-4%	-5%	12%	19%	0%	-1%	-9%	-15%	9%	-9%	-11%	-4%	-14%
Colorado River near Granby, CO (09019500)	-22%	5%	-8%	8%	13%	2%	9%	-6%	-10%	10%	-8%	-14%	-5%	-15%
Colorado River near Dotsero (09070500)	-21%	-6%	-5%	14%	19%	-2%	1%	-10%	-18%	8%	-14%	-12%	-4%	-14%
Colorado River near Cameo (09095500)	-21%	-6%	-5%	14%	17%	-6%	-1%	-10%	-19%	5%	-17%	-12%	-6%	-14%
Homestake Creek at Gold Park (09064000)	-21%	-5%	-5%	14%	18%	-10%	-4%	-11%	-23%	2%	-20%	-15%	-9%	-17%
Roaring Fork River near Aspen (09073400)	-10%	0%	-1%	14%	17%	-4%	2%	-3%	-13%	5%	-12%	-6%	-2%	-7%
South Platte														
S.Platte River above Spinney Mountain Reservoir (06694920)	-25%	-7%	-6%	17%	23%	-7%	-10%	-18%	-29%	8%	-14%	-20%	-11%	-27%
South Platte River below Cheesman Reservoir	-27%	-8%	-7%	19%	31%	-5%	-14%	-21%	-33%	17%	-11%	-22%	-12%	-34%
South Platte River at South Platte	-27%	-8%	-7%	19%	33%	-3%	-13%	-21%	-32%	19%	-10%	-23%	-12%	-34%
South Platte River at Henderson (06720500)	-28%	-10%	-9%	16%	29%	-5%	-12%	-22%	-31%	15%	-12%	-24%	-13%	-34%
South Platte Tributaries														
Cache la Poudre River at Mouth of Canyon (06752000)	-27%	-7%	-6%	15%	20%	7%	7%	-10%	-14%	14%	-8%	-17%	-4%	-16%
St. Vrain Creek at Canyon Mouth near Lyons	-21%	-5%	-5%	12%	20%	5%	2%	-11%	-17%	16%	-4%	-14%	-4%	-20%
Big Thompson River at Mouth of Canyon near Drake (06738000)	-16%	-7%	-7%	18%	25%	7%	8%	-12%	-18%	19%	-7%	-16%	-5%	-20%
Boulder Creek at Orodell	-19%	-4%	-5%	12%	19%	4%	0%	-10%	-14%	14%	-3%	-12%	-4%	-16%
Arkansas River														
Arkansas River at Salida (07091500)	-19%	-6%	-6%	12%	16%	-10%	-7%	-14%	-23%	1%	-19%	-15%	-11%	-21%

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- Colorado Springs Utilities
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- Northern Colorado Water Conservancy District

Joint Front Range Climate Change Vulnerability Study

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