Appendix U

Climate Technical Work Group Report

This appendix contains a copy of a forthcoming report entitled *Review of Science and Methods for Incorporating Climate Change Information into Bureau of Reclamation's Colorado River Basin Planning Studie*s. The report provides a summary of an assessment of the state of knowledge with regard to climate change and modeling for the Colorado River Basin and provides recommendations on future research and development needs. This report will be a forthcoming Reclamation publication with no change in content; however the formatting will be changed from that used in this appendix. This report was prepared by the Climate Technical Work Group that was empanelled by Reclamation to provide information on climate science and future climate conditions and their potential impact on the Colorado River. The Climate Technical Work Group included climate experts from the University of Colorado (National Oceanic and Atmospheric Administration – Western Water Assessment), the University of Arizona, the University of Nevada – Las Vegas, the University Corporation for Atmospheric Research, Reclamation, and Hydrosphere Consultants, Inc.

Bureau of Reclamation

Climate Technical Work Group

Review of Science and Methods for Incorporating Climate Change Information
into Reclamation's Colorado River Basin Planning Studies

Final Report

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U.1 Executive Summary

U.1.1 Background

The potential impacts of climate change and hydrologic variability on the Colorado River have been subjects for discussion for many years. The continuing drought in the Colorado River Basin coupled with recent advances in scientific knowledge regarding the potential impacts of climate change has heightened this interest.

The recent drought has emphasized that the principal influence on water availability is the amount of runoff in the basin. The conventional assumption used in water resources planning is that the past record of runoff can be used to represent future conditions; that the future will look like the recent past. Reclamation, like most water management agencies, has, until recently, relied on this conventional assumption in its planning activities.

Reclamation has recognized the limitations of the conventional assumptions for some time, but the continuing drought conditions accelerated efforts in the agency to investigate alternative assumptions which may be used in its planning and operations. Furthermore, considerable evidence from paleo records concluded that the observed record of the last 100 years did not capture the full range of variability of historical streamflows in the Colorado River.

Reclamation's Lower Colorado Region initiated a multi-faceted research and development program in 2004 to enable the use of other methods for projecting possible future inflow sequences for Colorado River planning studies. The research and development effort has been designed to provide information for the near-term (e.g., some facets have already been completed), as well as the longer-term that involves collaboration with other research organizations (e.g., National Oceanic & Atmospheric Administration and United States Geological Survey). The effort is focused on two key areas:

- collaboration with other federal agencies and universities to conduct research to gain knowledge and understanding of the potential impacts of climate change and climate variability on the Colorado River, and

- improvement of Reclamation's decision support framework, including modeling and data handling capabilities, in order to utilize the new information when it becomes available.

To assist in the direction and prioritization of these efforts, particularly over the next few years, a group of experts in meteorology, climate and hydrology, referred to as the Climate Technical Work Group (Work Group), was empanelled to provide information to Reclamation about the state of knowledge regarding climate science and future climate conditions and their impact on water resources, particularly on the Colorado River Basin.

In addition, the Work Group ran parallel with and informed Reclamation's development of the final environmental impact statement (EIS) for the proposed adoption of interim operational guidelines for Lake Powell and Lake Mead on the feasibility of considering long-term projections of climatic conditions in its assessment of alternative proposed guidelines. Contributions from the Work Group as well as the research and development program were invaluable in advising the analysis and content in the final EIS to address future hydrologic variability and the potential for increased hydrologic variability due to climate change.

Reclamation convened a meeting of the Work Group on November 8, 2006. In addition to the outside expert invitees, a number of Reclamation staff and contractors also attended the meeting. The members of the Work Group and attendees at this meeting are listed in Attachment 1. The November 8 meeting provided the opportunity for a face-to-face discussion between the climate experts and Reclamation staff. Following the meeting, a smaller group of Reclamation staff, contractors and outside experts developed this report. The members of this drafting group are listed in Attachment 1. The drafting group developed an initial outline which was circulated to the entire Work Group in February 2007. Based on feedback on the outline, a draft of this report was developed and circulated to the Work Group for review in April 2007. Comments were received from the Work Group and other interested parties including climate scientists, water resource engineers, and Reclamation personnel. The Work Group revised the document and transmitted it to Reclamation in its final form in August 2007. Reclamation pre-published the final report as an appendix to the final EIS for the proposed adoption of Colorado River interim guidelines for Lower Basin shortages and coordinated operations for Lake Powell and Lake Mead in October 2007.

U.1.2 Findings

U.1.2.1 State of Climate Change Science

There is strong scientific consensus that the earth has been warming, that this warming is driven substantially by human emissions of greenhouse gases, and that warming will continue. Climate models project that temperatures will increase globally by 1 to 2ºC in the next 20-60 years. The projections are fairly consistent for the next 20 years, with a 1ºC increase, but exhibit larger uncertainty in the 40-year projections. Scientists agree on some of the important broad-scale features of the expected hydrologic changes, the most likely of which will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures.

U.1.2.2 Potential Impacts to the Colorado River Basin

The impact of climate change on the region of the Colorado River Basin (CRB) is less certain; however, it is expected that regional temperatures will also increase. Regional precipitation response is less certain with comparable evidence suggesting wetter or drier conditions. There is some consistency to indications of a general drying for mid-latitude regions such as the CRB, but this indication must be tempered by the limited precision of existing atmospheric models in resolving the topography of the southwestern U.S.

The potential impacts of climate change on the CRB's water resources have been a subject of research for several decades. Although an aggregate message from these studies may be that a decrease in runoff can be expected, runoff response across these same studies *ranges from increase to decrease*. These studies show that system storage is very sensitive to changes in mean inflows as well as to sequences of dry and wet years.

The degree to which current methods can provide reliable information about future streamflow variability remains a question.

U.1.2.3 Options for Relating Climate Change Projections to Reservoir Operations

There are several options available for translating climate projections into operations response information. The three core steps for long term operations analysis under assumed climate change include: (i) selecting a simulated climate scenario that overlaps with observed historical conditions and extends into a future planning horizon, has been bias-corrected, and has been downscaled to a basin-relevant resolution; (ii) relating the downscaled climate conditions over the basin to natural runoff response; and (iii) relating simulated natural runoff response to water supply and operations response. After these core steps are defined, it is necessary to consider other options about how variability in water resources conditions will be addressed.

In addition to the uncertainties inherent in projections of greenhouse gas concentrations, and in simulation of future climate conditions using General Circulation Models (GCMs), there are various uncertainties associated with relating climate projections to runoff and operations. These include the assumptions on converting simulated climate time series into a meteorological input sequence for runoff analysis, assumptions on how to convert meteorological input to runoff, assumptions on how to represent system operations within the operations model under a changing climate, and assumptions on future land use and land cover.

U.1.2.4 Paleoclimatic Information

Paleoclimatic information for the Colorado River basin is extensive, with the most notable, and reliable, streamflow reconstructions being for Lees Ferry (dividing point between Upper and Lower basin). The streamflow reconstructions there go back as far as AD 762 and have been used to create hydrologic scenarios for planning studies. The main limitation in the use of paleoclimatic information is when reconstructed flow values are beyond the “predictor space” on which the model is based. These values may be less reliable than other reconstructed values. There is an emerging area of research on how paleoclimatic information can be used with climate change projections. The main idea is to combine the variability in the paleohydrologic records with the more certain future warming for assessing possible future scenarios.

U.1.2.5 Interannual and Interdecadal Variability

There is an increasing awareness that in addition to gradual changes (long-term trends) in climate conditions, there is also a large degree of interannual and interdecadal variability in climate, which may dominate the climate experienced in a basin in the short term (10-20 years in the future). The well known El Niño-Southern Oscillation (ENSO) has linkages in the Lower Basin where El Niño events bring generally wetter conditions and La Niña events bring drier conditions. A limitation on research relating interannual and interdecadal variability is the relatively short time periods available for the analysis. The use of paleoclimatic data may enhance the understanding of these multidecadal phenomena. The impacts from interannual and interdecadal climate variability on streamflow may be significant for planning studies with short planning horizons (e.g., 20 years). This could be just as important as evaluating the impacts of climate change that may not really be noticed in the basin for 20-50 years.

U.1.3 Recommendations

U.1.3.1 Planning Studies

Shorter Look-Ahead Studies: For studies and management decisions involving shorter look-ahead horizons (e.g., less than 20 years), an appropriate level of analysis might involve a qualitative discussion of climate change and interannual-to-decadal variability within the study's look-ahead horizon. If the role of shorter-term climate is critical to the study, the proposed qualitative discussion might be accompanied by a quantitative sensitivity analysis based on instrumental record and paleoclimate evidence.

Longer Look-Ahead Studies: For studies and decisions concerned with greater than 20-year look-aheads and being evaluated on the near-term, it is suggested that a quantitative sensitivity analysis be conducted on operations response to projected climate change using approaches previously mentioned in ES 2.3. By comparing system performance using projected climate change hydrology to historical hydrology, useful knowledge about system sensitivity should be ascertained.

U.1.3.2 Research and Development

Improved Availability and Temporal Resolution of Regional Climate Projection Datasets: Currently, there is limited access to bias-corrected and downscaled climate projection datasets over the Colorado River basin. An archive of bias-corrected and spatially downscaled GCM outputs should be made available to researchers and the public. In addition, as dynamically downscaled datasets become available, these datasets should be added to the archive.

Improved Ability to Model Runoff Under Climate Change: Currently there are only a few runoff models available to generate CRB natural flow given climate inputs, and Reclamation does not have easy access to these models. Reclamation needs to build internal staff expertise with available runoff model applications in the basin, and build coalitions with external groups that use such applications. Ideally, such runoff applications would also report other hydrologic processes' response to climate change (e.g., soil moisture, evapotranspiration, groundwater interactions with surface water).

Investigate Paradigm for Colorado River basin Precipitation Response: While there is an evolving paradigm for how the American Southwest and other existing dry subtropical areas of the globe should respond to climate change, it is not clear how nearby relatively wet mountainous areas such as the Rockies should respond. In addition, the ability of GCMs to simulate future precipitation conditions at this spatial scale is questionable. Reclamation should encourage and support work to improve scientific understanding of precipitation response to climate change.

Diagnose and Improve Existing Climate Models Before Adding Additional Features:_Given known GCM limitations in simulating regional precipitation, climate research groups should focus a portion of their efforts on diagnosing and correcting biases in the current collection of climate models.

Investigate Changes in Modeled Climate Variability at Multiple Time Scales: It is well appreciated that the Colorado River is sensitive to changes in mean flow. However, variability as represented by drought spells, wet refill periods, and extended decadal and longer periods of above and below-average flow are also critical for determining system yield. Therefore, investigation of such variability in modeled sequences of precipitation, runoff and other climatic variables is critical.

Improve Understanding of Surface water, Groundwater and Land cover Interaction: Because rivers and groundwater are intimately connected, understanding the entire recharge process and its response to climate change is critical. Hence, research is required on groundwater recharge and movement at scales relevant to regional runoff analysis, and this in turn requires understanding the aggregate process of mountain block recharge and the role of riparian and root zone vegetation. The latter leads to additional research questions on how basin land cover and natural evapotranspirative demand will respond to global climate change.

Improve Prediction of Interdecadal Oscillations: The predictability of interdecadal climate oscillation phases and their associated hydrologic impacts on the Colorado River basin are not well understood. Shorter-term planning may be more influenced by these oscillations than by projected changes in climate means. Reclamation should actively support, either materially or otherwise, efforts in the science and applications community to advance knowledge in this area.

Investigate use of Paleo Record to Inform Modeled Streamflow Variability: Reclamation has funded some research on how to use information from the paleoclimate record in modeling studies. While the past will not repeat, the paleo record contains a wealth of information on natural variability that should not be ignored. For example, there may be valuable ways of combining paleo data with modeled and or historical data to modify the variability in these sequences in useful ways.

Interact with Federal Climate Change Science Program and Other Climate Change Research Initiatives: Although Reclamation can pursue and fund some of the Research and Development work described above, many of these problems will require the assistance of the larger scientific and engineering community. The Department of the Interior is one of thirteen agency members of the approximately $2 billion per year federal Climate Change Science Program, the umbrella under which all federal climate change activity is pursued. In order to raise the profile of these issues and obtain resources to help solve them, Reclamation should engage the CCSP. In addition, Reclamation should collaborate with NOAA, the National Center for Atmospheric Research, and the University research community.

U.2 Introduction

U.2.1 Process and Context

As part of its responsibility to manage water resources within the Colorado River basin, The U.S. Department of Interior, Bureau of Reclamation (Reclamation) is continuously evaluating the effect of operating procedures and policies in the basin. The primary effects of changing operating rules are changes in reservoir releases, river flows, reservoir contents, water quality and water deliveries to end users. These primary effects influence economic, social and environmental conditions. Reclamation makes its evaluation of the primary effects of operating policies with modeling studies that simulate the effect of operating rules on system conditions and water availability. Additional models are used to estimate secondary effects.

Conventional water resources planning has been based on two assumptions:

- The observed history of hydrology for a particular system adequately captures the past mean and variability of water supply for that system

- The past mean and variability of water supply is representative of future conditions.

Reclamation has recognized the weakness of the conventional assumptions for some time, but the acute drought conditions that began in 2002 accelerated efforts in the agency to investigate alternative assumptions on which planning and operations could be based. By 2004, the problem with the conventional assumptions had been clearly demonstrated when the reservoirs on the Colorado River reached states that could not have been simulated by conventional approaches in 2002.

The recent drought also brought attention to the need to develop operating rules to allocate the water of the lower Colorado River in times of shortage. Reclamation, the Basin States and the Secretary of the Interior realized that it was necessary to adopt specific operational guidelines to address the operation of Lake Powell and Lake Mead during drought. Accordingly, the Secretary of the Department of the Interior acting through the Bureau of Reclamation, Upper and Lower Colorado Regions (hereinafter, Reclamation), proposed adoption of specific Colorado River Lower Basin (Lower Basin) interim shortage guidelines and coordinated reservoir management strategies to address operations of Lake Powell and Lake Mead, particularly under drought and low reservoir conditions. The guidelines would change the way the reservoir system on the river is operated and define circumstances where deliveries to certain water users would be curtailed. Such operational changes may affect reservoir storage levels and releases at Lake Powell and Lake Mead, which in turn may subsequently affect river flows, available water supplies, and other resources.

The Secretary has designated Reclamation as the lead federal agency for the development and implementation of the proposed interim guidelines, and for the purpose of compliance with the National Environmental Policy Act of 1969 (NEPA). Reclamation and five cooperating federal agencies have prepared a Draft EIS (Draft Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated

Operations for Lake Powell and Lake Mead, U.S. Department of the Interior, Bureau of Reclamation, Upper and Lower Colorado Regions; Reclamation 2007) to provide an opportunity to develop the information needed to analyze and consider trade-offs inherent in the proposed action.

Five alternatives have been considered and analyzed in the Draft EIS. The potential hydrologic effects of the alternatives were evaluated through the use of water resources modeling studies. The water resources modeling served as the basis for other analyses of the potential effects of the alternatives on other environmental resources. In addition to making these analyses, Reclamation conducted sensitivity analyses using alternative assumptions regarding the hydrology of the Colorado River basin. Three alternative hydrologic scenarios were used in these sensitivity analyses, two based on reconstructions of pre-historic flows (paleohydrology) and one based on synthesizing new scenarios based on the statistics of the observed record (stochastic hydrology).

Reclamation recognized that the three sensitivity analyses did not directly respond to growing concerns that global climate is changing and with that change would come corresponding changes in the hydrology of the Colorado River basin. Impacts arising from the proposed actions are sensitive to the magnitude and timing of the natural streamflows in the Colorado River, which in turn would be influenced by any changes in climatic conditions.

Reclamation wished to evaluate the potential impact of climate change on water availability and environmental conditions in the Colorado Rive basin, but recognized that there is considerable scientific uncertainty about the precise nature of climate change and its effects in the basin. Reclamation also did not know what tools might be available to evaluate the impact of climate change. The Lower Colorado River Region of Reclamation decided to empanel a group of experts in meteorology, climate and hydrology, referred to as the Climate Technical Work Group (Work Group), to consult with the agency and assist it in addressing these questions. The Upper Colorado River Region and the Technical Services Center of Reclamation also participated in the Work Group process.

Reclamation asked the Climate Technical Work Group to provide information to Reclamation about the state of knowledge regarding climate science and future climate conditions and their impact on water resources. In addition, information regarding the feasibility of considering long-term projections of climatic conditions in its assessment of alternative proposed guidelines and strategies were considered.

U.2.2 Description of Document

This document summarizes the state of climate science and how future climate conditions may impact the water resources of the Colorado River basin. Section W.2.0 describes the Climate Technical Work Group, the charges provided to the Work Group, and the process used in preparing the final report. Section W.3.0 provides background information on how climate assumptions are currently represented in long-term planning. Section W.4.0 summarizes the state of science on observed and projected climate conditions. Section W.5.0 summarizes the various studies that have evaluated the potential impacts of climate change on the water resources of the Colorado River basin. Section W.6.0 describes methods that may be used for relating climate information to long-term water resources planning. Section

W.7.0 summarizes available paleoclimatic information, some of which might serve as proxy information for future climate possibilities. Section W.8.0 summarizes the state of science on shorter- to longer-term climate oscillations and variability that also impact water resources. Lastly, Section W.9.0 provides a summary of key themes from each section, identifies critical issues that warrant further investigation, and offers recommendations for how climate change and variability information could be further incorporated into Lower Colorado (LC) Reclamation's longer term planning efforts.

U.3 Climate Technical Work Group

U.3.1 Formation and Charge

Beginning in September, 2006, Reclamation identified potential members of the Climate Technical Work Group and began extending invitations for participation in the Work Group process to those candidates. Twelve climate scientists and hydrologists were invited to participate on the Work Group. These invitees are listed in Attachment 1.

Reclamation asked the Work Group to provide information in the following areas:

- The state of knowledge that exists regarding long-term projections of climatic conditions, including the state of knowledge regarding climatic processes, and the state of knowledge regarding numerical simulation of long-term future conditions (Section W.4.0).

- What methods would be appropriate, timely and cost-effective to quantify future conditions, including quantifying the uncertainty arising from the state of knowledge of climate processes and numerical representations of climate processes?(Sections W.4.0 and W.5.0)

- The extent to which existing reconstructions of paleo streamflows could be used, alone or in conjunction with long-term climate projections, in the evaluation of alternative guidelines and strategies. (Section W.7.0)

U.3.2 Process

Reclamation convened a meeting of the Work Group on November 8, 2006. In addition to the outside expert invitees, a number of Reclamation staff and contractors also attended the meeting. The attendees at this meeting are listed in Attachment 1.

The November 8 meeting provided the opportunity for a face-to-face discussion between the climate experts and Reclamation staff. It was conducted informally, with considerable give and take. The meeting began with a presentation by Reclamation staff about the purpose of the Work Group and its charge. Reclamation suggested that a report from the Work Group would be a useful work product. Reclamation provided a comprehensive orientation to the Colorado River basin, including the hydrology of the basin, the Law of the River, water use in the basin, the water resources facilities in the basin, and operations. Discussions regarding operations addressed the recent drought and the current process of developing shortage guidelines. Subsequent discussions focused on the science of climate change and the likely impacts of climate change on the hydrology of the Colorado River basin. Considerable attention was given to the uncertainties inherent in projections of temperature and precipitation in the Basin.

Following the meeting, Reclamation convened a group of Reclamation staff, contractors and outside experts to develop an initial draft of a report from the Work Group. The members of this drafting group are listed in Attachment 1. The drafting group initially developed a suggested outline for this report, which was circulated to the entire Work Group in February 2007. The drafting group subsequently prepared a draft of this report, which was circulated to the Work Group in April 2007 for review. Comments were received from the Work Group and other interested parties including climate scientists, water resource engineers, and Reclamation personnel. A revised version of the document was finalized in August 2007.

U.4 Recent Treatment of Hydrology and Climate by LC Reclamation in Long-Term Planning Analyses

U.4.1 Recent LC Reclamation Requirements

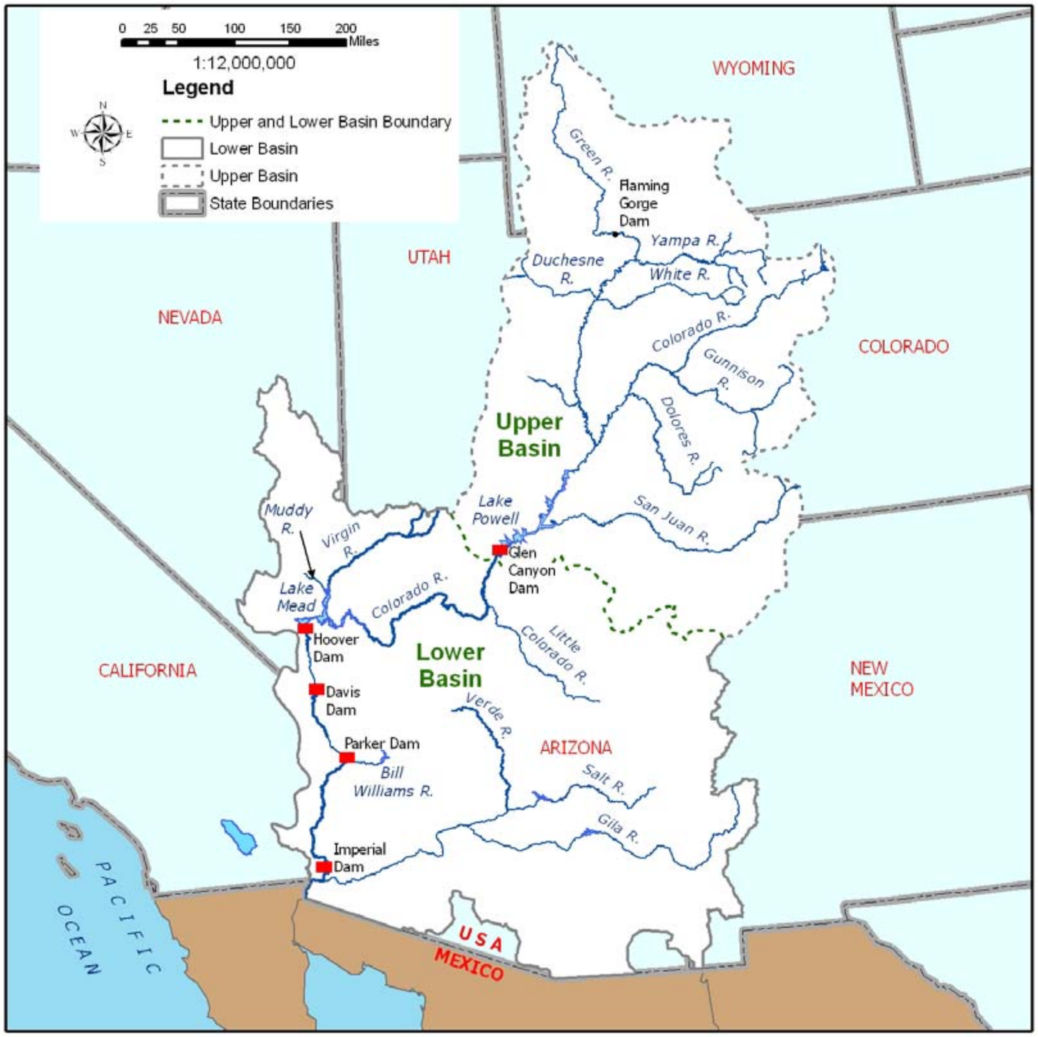
The Colorado River basin is located in the southwestern United States, as shown on Figure U-1, and occupies an area of approximately 250,000 square miles. The Colorado River is approximately 1,400 miles in length and originates along the Continental Divide in Rocky Mountain National Park in Colorado. The basin has been divided into Upper Basin and the Lower Basin, as shown in Figure U-1. Reclamation is the agency that has been designated to act on the Secretary's behalf with respect to the operation of Glen Canyon Dam and Hoover Dam. More information about the Colorado River and its water resources can be found in Section 1.7 of the Draft EIS (Reclamation, 2007).

As part of its responsibility to manage water resources within the Colorado River basin, Reclamation is continuously evaluating the effect of operating procedures and policies in the basin. The primary effects of changing operating rules are changes in reservoir releases, river flows, reservoir contents and water deliveries to end users. These primary effects influence economic, social and environmental conditions. Reclamation makes its evaluation of the primary effects of operating policies using a water resources system model of the Colorado River that simulates the effect of operating rules on system conditions and water availability. Additional models are used to estimate secondary effects.

U.4.2 Colorado River Simulation System (CRSS)

Future Colorado River system conditions are simulated using the Colorado River Simulation System (CRSS). CRSS is a simulation model consisting of a database and a modeling code. The database describes the physical configuration of the natural and man-made features of the Colorado River system, the operating rules for the man-made features, the natural gains and losses of water that enter and leave the system, and the water used by or requested for use for human activities. The modeling code simulates the physical processes and institutional drivers that determine the system conditions, according to the data contained in the database. The model is run to determine system conditions for a given scenario, as described by the input data. For some resource analyses, results from CRSS are used as input to additional modeling studies that are required to characterize impacts to other resources.

Figure U-1
The Colorado River basin



CRSS simulates 12 reservoirs, 115 water delivery points and 29 inflow points. It simulates water entering the system, storage in system reservoirs, releases from storage, river flows, natural and man-caused losses of water, and the water demands of and deliveries to water users in the basin states and Mexico. The input data for the model include monthly natural inflows, various physical process parameters (such as the evaporation rates for each reservoir), initial reservoir conditions, and the diversion and depletion schedules for entities in the basin states and Mexico. The operating rules are also input for each scenario analyzed. CRSS is fully described in Appendix A of the Draft EIS (Reclamation, 2007).

The principal independent input to the model are data representing the patterns of inflows at the 29 inflow points. These inflows define the water inventory that will be managed in the system for beneficial use and environmental protection. Other inputs, such as water demands and operating rules, are controlled principally by human decisions. Despite differences between operating rules among scenarios, the future conditions of the Colorado River system (especially water levels at Lake Mead and Lake Powell) are most sensitive to future inflows.

U.4.3 Climate-related CRSS Inputs

The hydrology of a watershed is driven by its climate. Liquid water is introduced to a watershed by precipitation of water vapor from the atmosphere and is continuously removed from the watershed in the form of water vapor through the processes of evaporation and evapotranspiration. These processes are said to “deplete” the available water in a watershed. Any remaining liquid water may leave the watershed as stream or groundwater discharge. Some water will be stored temporarily in a watershed as groundwater, as ice or snow, or in man-made impoundments. Evapotranspiration, as used here, is the sum of evaporation of water from soil and transpiration of water from plants as they grow. Natural landscapes and agriculture deplete water through evapotranspiration. Water is evaporated from the surface of natural and man-made water bodies and through the operation of industrial processes. Depletion of available water supplies is the unavoidable cost of putting water to uses that benefit human beings.

As climate changes so will the hydrology of a watershed. Changes in precipitation, radiation and temperature will affect the water balance in a watershed and hence will affect the net runoff leaving that watershed. Changes in precipitation change the water supply input to a watershed. At regional scales, the dominant effect on the rate of evaporation is the availability of radiant energy at the evaporating surface. Air temperature is often used as a surrogate for energy input, and also influences convective heat transport. Changes in radiation and temperature will change the magnitude and pattern of evaporative water losses that deplete outflows from a watershed. In snowmelt-driven basins, changes in radiation and temperature will affect the fraction of precipitation that falls as snow and the rate and timing of snowmelt and will thereby change the pattern of outflows. Changes in radiation, temperature and precipitation will also change the magnitude and patterns of some human water uses. The effect of climate on streamflow is discussed in more detail in Section W.5.0.

Like any other watershed, the hydrology and water resources of the Colorado River basin are driven by climate and therefore are sensitive to climate change. Inputs to CRSS reflect past climate, including past climate variability, but do not reflect projected changes in climate. The input variables for CRSS that are sensitive to climate conditions are inflows and losses, water use by humans, and reservoir evaporation. These are described in the following paragraphs.

U.4.3.1 Inflows

CRSS represents the natural gains and losses to the river system at 29 “inflow points” throughout the basin. Fourteen of these inflows are “rim inflows”, which represent physical flow in a river reach at the outermost perimeter of the watershed. The remaining fifteen inflow points are incremental gains and losses, which represent the amount of water that is introduced to or removed from a particular river reach by “natural” processes. Incremental gains and losses include inflows from smaller tributaries and depletions along the reach. All inflows are expressed as monthly volumes.

These values represent "natural flows" that in turn represent the conditions that would have existed if all man-caused water uses and operational effects (e.g. reservoir storage and release) had not occurred. The natural flows include the effect of natural processes including depletions arising from evapotranspiration and the effect of storage and recharge to and from groundwater.

U.4.3.2 Water Use

Water use can be categorized as natural or social. Natural water use includes, for example, depletion of river flows by riparian vegetation or upland vegetation in a watershed. Social water use includes the demands of agriculture, industry and municipalities. CRSS incorporates natural water uses into the natural flow values representing rim inflows and incremental gains and losses. Social water uses, are driven by management choices and are represented explicitly in the model as variables.

Changes in climate will affect natural water use, but the response of water use to climate change is complex and varies on different time scales. The immediate response to changes in radiation and temperature is change in depletions arising from evaporation and evapotranspiration. Changes in precipitation will not affect depletions directly, but rather change the water supply. The longer term impacts of changes in radiation and temperature, and in the depth and intensity of precipitation will be changes in vegetation and even soil structure, subsequently affecting natural gains or losses in the watershed and riparian systems.

Changes in radiation, temperature and precipitation will change the patterns of diversion and depletion of water applied to social uses. This is primarily driven by changes in the intensity of evapotranspiration from agriculture and outdoor domestic use, but is also influenced by changes in the growing season brought on by changes in temperature. Of indoor domestic and industrial uses, depletions from uses such as cooling and reservoir storage (in the form of evaporation from the reservoir surface) are likely to be affected by changing climate. Because changes in climate will change the pattern of diversion (required to satisfy the irrigation requirements of crops or landscaping plants), the pattern and volume of direct flow diversions, releases from reservoirs and return flows will also change. These responses are driven by economic and institutional factors and are difficult to predict.

The impact of these effects on water use in the Upper Basin will be changes in the pattern and annual volume of inflows to Lake Powell. Section W.5.0 discusses some of the assessments that have been made about the effects of climate change on streamflows in the Colorado River basin. However, quantifying the changes in inflows to Lake Powell is complicated by the economic and institutional responses to the changes in water supply and irrigation requirements.

Because deliveries to Lower Basin water uses are defined by institutional constraints (e.g. contracts and decrees), changes in water use in much of the Lower Basin will not directly change the total amount of water released from system reservoirs. Changes in the seasonal pattern of water deliveries in the Lower Basin could change the timing of operational trigger events in Lake Mead and thus induce subtle but long-lasting effects in upstream reservoir operations. Changes in water use along the Lower Basin tributaries to the Colorado River below Lake Mead will have a more substantial effect on system operation, since changes in the amount and timing of return flows from these uses will change the amount and timing of releases from Lake Mead that are required to meet the water delivery requirements to Mexico.

U.4.3.3 Reservoir Evaporation

CRSS represents the net evaporation (evaporation adjusted for precipitation falling directly on the reservoir) from the water surface of reservoirs. Thus, changes in precipitation, radiation or temperature will affect the net evaporation simulated by CRSS.

U.4.4 Recent LC Reclamation Hydrologic Scenarios

Reclamation has used four different approaches to represent streamflow hydrology in modeling studies of the Colorado River system. These four approaches are summarized below. More detail on each approach can be found in Appendix N of the Draft EIS (Reclamation, 2007).

U.4.4.1 Direct Natural Flow Record (DNF)

Reclamation has developed a database of historical natural flows, gains and losses at the 29 inflow points required by CRSS. This database covers a period from October 1905 through December 2004 (water year 1906 through water year 2004). Analyses using this database are run on a calendar year basis and cover the period January, 1906 through December, 2004.

Reclamation has recognized that due to the natural variability of streamflows, the exact pattern of flows captured in the historical natural flow dataset is unique and will not occur again. In an effort to incorporate variability in system conditions that would reflect the natural variability of streamflow, Reclamation adopted a block bootstrap approach for resampling the historical record, known as the Indexed Sequential Method (ISM) (Reclamation, 1985; Ouarda et. al., 1997). ISM cycles through each year in the natural flow record and extracts a sequence of flows beginning at that year and extending through the desired scenario length. If a flow sequence overlaps the end of the natural flow data set (calendar year 2004) the method wraps around to the start of the natural flow record (calendar year 1906) and continues the sequence from that point. Because there are 99 years in the natural flow record the ISM method can create 99 distinct flow sequences. The ISM method applied to the 1906 to 2004 natural flow record is referred to as the Direct Natural Flow Record (DNF) approach.

The strengths of this method are that it is easy to implement, it is understandable, and it has been widely accepted by stakeholders on the Colorado River. However, each DNF scenario consists only of annual and monthly flow magnitudes and sequences that have occurred in the observed record, with the exception of new sequences being generated as a result of the wrap.

Reclamation has relied for some time on the DNF approach for planning in the Colorado River basin. Because it recognized the limitations in the DNF approach, Reclamation has for several years been conducting or sponsoring research aimed at developing methods that do not suffer from the same limitations as the DNF approach. In evaluating alternative shortage policies Reclamation has conducted sensitivity analyses using three alternative hydrologic scenarios, which are described briefly in the following paragraphs.

U.4.4.2 Non-Parametric Paleo Conditioned (NPC)

This technique also applies a bootstrap re-sampling to the historical natural flow record, but in this case the re-sampling is done on a year-by-year basis and the selection is conditioned on hydrologic state sequences (i.e., wet or dry) that are modeled based on a paleo reconstruction of streamflows at Lees Ferry. In the NPC method the magnitudes of individual flows are taken from the historical natural flow record, but the sequences of flows reflect sequence properties characteristic of the paleo reconstruction. The result is that wet and dry spells represented by the NPC method are different than those represented by the DNF or the direct paleo (DP) (described below) method. In particular, the NPC method will represent longer dry spells than are present in the historical natural flow record because longer dry spells are present in paleo reconstructions of streamflow in the Colorado River basin. Because the magnitudes of individual flows are taken from the historical natural flow record, the NPC method will not generate flow magnitudes beyond those in the observed record. The NPC method was used to generate 125 traces, each of 53 years in length.

This method is described in detail in Appendix N of the Draft EIS (Reclamation, 2007) and in Prairie (2006).

U.4.4.3 Parametric Stochastic Natural Flow Record (PS)

This technique uses parametric stochastic methods to fit the observed natural flows (1906-2003) to an appropriate set of stochastic models for streamflow generation and disaggregation. A parameter fitting procedure is applied to fit the observed natural flow to a contemporaneous autoregressive order 1 (CAR(1)) model. The PS method was used to generate 100 traces, each of 53 years in length. The PS method can generate both flow magnitudes and sequences not seen in the observed record, though the generated scenarios will be statistically similar to the observed record. The PS method can generate flow magnitudes much larger or much smaller than those in the observed record, which may be difficult to justify on a physical basis.

This method is described in more detail in Appendix N of the Draft EIS (Reclamation, 2007) and in Salas (1985) and Lee et al. (2006).

U.4.4.4 Direct Paleo (DP)

This technique uses a reconstruction of streamflow at Lees Ferry by Woodhouse, et al. (2006) which has been disaggregated to the 29 inflow points using a nonparametric disaggregation method (Prairie et al., 2006). The reconstructed trace used in this method is the same trace used in the NPC method, but in the DP approach both the magnitudes and sequences of flows are taken directly from the paleo reconstruction, whereas in the NPC method only the characteristics of the state sequence are taken from the paleo reconstruction, and the values result from resampling the observed streamflow conditioned on the previous resampled streamflow and the current and previous sequence properties. The DP approach will represent the longer droughts indicated by paleo reconstructions, but will also represent individual annual flow magnitudes that are not present in the historical natural flow record. Unlike the other methods, the long-term mean flow produced by the DP method will be different (in this case lower) than that seen in the observed record.

This method is described in more detail in Appendix N of the Draft EIS (Reclamation, 2007).

U.4.5 Climate Assumptions Implied by Hydrologic Scenarios

As noted earlier, the conventional water resources planning has been based on two assumptions: that the observed history of hydrology for a particular river system adequately captures the past mean and variability of water supply for that system, and that the observed history is representative of future conditions. Implicit in these conventional assumptions is the premise that climate, which drives hydrology, is static. Only in recent years have a significant fraction of water resources managers begun to depart from this premise and find ways of incorporating information about the potential hydrologic impacts of climate change in water resources planning.

All four hydrologic scenarios currently in use by Reclamation are based on the implicit assumption that the future mean and variability of streamflow can be adequately characterized by the statistics of past observations. The DNF and PS approaches assume that the last roughly 100 years characterize future conditions while the NPC and DP approaches extend that period to approximately 500 years. These scenarios do not reflect any probability that the future mean and variability of streamflows will differ from past values due to changes in future climate conditions. However, as discussed in Section W.7, the paleohydrology reflected in the NPC and DP approaches could be adapted to reflect alternative assumptions regarding future climate that are consistent with the findings of recent climate research and modeling.

U.5 State of Science: Historic and Future Climate

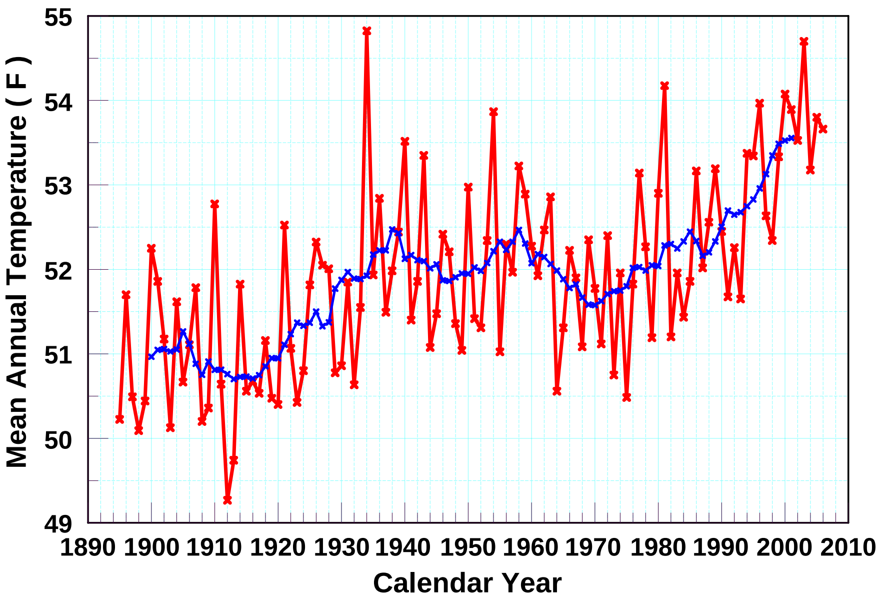
U.5.1 Historical Climate of the Colorado River Basin

One of the motivations for considering climate change implications for Colorado River basin water management is that changes in hydroclimatological conditions have already been expressed in the historical records. Through a variety of statistical methods, modeling efforts, and analytical processes, researchers have begun to identify and quantify trends within environmental time series and, in some cases, begun to forecast future climate trends. Recent climate trend research has focused on time series of streamflow, temperature, precipitation, and snow water equivalent (SWE) time series.

U.5.1.1 Temperature Trends

Trends in temperature for the Colorado River basin were summarized in the recent National Research Council (NRC, 2007) study. Figure U-2 displays the annual average air temperature for the entire Colorado River basin from 1895-2006. Overall there has been an approximately 1.6OC increase in the 11-year running mean. The increases primarily occurred during the periods 1920 to 1940 and 1970 to the present. These trends are also consistent with those seen in regional and global temperature records. However, the trends in the Colorado River basin are the largest in the continental U.S. when expressed as standard deviations. The significance of increase temperatures on the regions snowpack and streamflow are discussed in following sections.

Figure U-2
Annual and 11-year Running Average Temperature for the Colorado River Basin

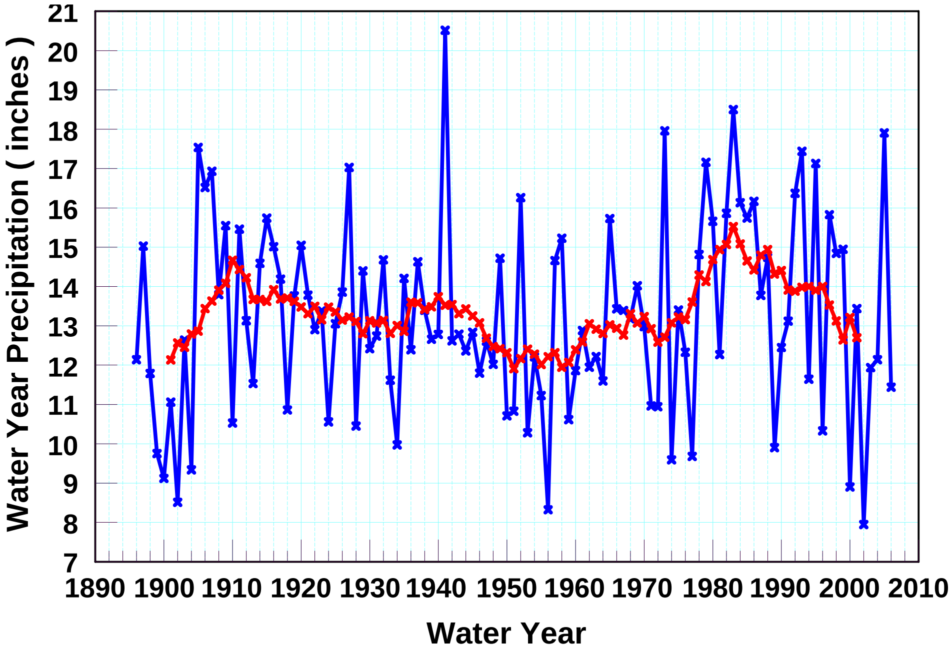


(Source: Western Regional Climate Center and NRC, 2007)

U.5.1.2 Precipitation (Rainfall and Snow) Trends

Trends in precipitation for the Colorado River basin were also summarized in the recent NRC (2007) study. Figure U-3 displays the annual precipitation for the Upper Colorado River basin from water years 1896 to 2006. There is a high degree of variability over the entire record. However, the past 30 years of record seem to have different variability as compared to the early part of the record. For instance, the lowest and highest annual precipitation amounts occurred in the past 30 years. In addition, there is evidence of more regimes of wet and dry episodes, lasting 4-6 years, since the middle 1970's compared with the previous 30-40 years. Even though there is more variability in the recent record, there does not appear to be an overall trend in the annual precipitation over the entire record.

Figure U-3
Annual and 11-year Running Average Precipitation for the
Upper Colorado River Basin from Water Year 1896 to 2006



(Source: Western Regional Climate Center and NRC, 2007)

It is also important to evaluate the form of precipitation (i.e., rain or snow). In the mountainous western U.S., approximately 50 – 70% of precipitation is observed as snow (e.g. Clark et. al. 2001). As a result, melting snowpack is an important and significant source of water for much of the west, particularly in the Upper and Lower Colorado River basins (e.g., Hamlet et al., 2005). Recent published research has studied the climate trend of snow data through the investigation of April 1st snow water equivalent (SWE) values, as April 1st is in many locations an accurate estimate of the peak of spring snowpack and total runoff (e.g., McCabe and Dettinger, 2002). Most studies in this review used observed National Resource Conservation Service (NRCS) SNOwpack TELemetry (SNOTEL) or snowcourse data. Table U-1 summarizes the time periods and parameters used in studies focused on snow and streamflow for the western United States.

Table U-1
Summary of Studies Evaluating Trends in Snow and Streamflow for the Colorado River Basin

Study Name	Time Period	Snow	Streamflow
Groisman et. al., 2001	1939-1999		
Hamlet et. al., 2005	1916-2003	Decreasing	earlier peaks
Kalra, et. al., 2007	1941-2004	Decreasing	
Lins and Slack, 1999	1944-1993		
Mote et. al., 2005	1950-1997	Decreasing	
Pagano and Garen, 2005	1901-2002		
Regonda et al., 2005	1950-1999	Decreasing	earlier peaks
Stewart et al., 2005	1948-2002	Decreasing	earlier peaks
Knowles et al., 2006	1949-2004	Decreasing	

Arrows indicate either increasing or decreasing trend. Blank cells indicate that there was no trend or the authors did not investigate that parameter.

All the studies (Mote, 2003; Hamlet et al., 2005; Regonda et al., 2005; Knowles et al., 2006; Mote, 2006; Kalra, 2007) noted a decline in April 1 SWE with a particular emphasis on high elevation stations. Mote (2003) attributes the decline in SWE observations in the Pacific Northwest and western U.S. (including the Colorado River basin) to increased temperature and a greater portion of precipitation falling as rainfall, particularly at elevations below 1800 meters. Mote et al., (2005) expanded upon the study presented in Mote, (2003) by using the Variable Infiltration Capacity (VIC) Model. In the Lower Colorado River basin, the VIC Model showed an increasing trend in SWE, sometimes in excess of 30% from 1950 to 1997. The Upper Colorado River had primarily a decreasing trend.

Regonda et. al. (2005) collected data from snowcourse sites over the period 1950 to 1999 in an attempt to quantify the timing of snowmelt with trends in hydroclimatic variables. April 1 SWE values from snowcourse sites spanning the western U.S. were correlated with streamflow stations in the Western United States. Regonda et. al., (2005) found decreases in SWE correlated to increases in temperature and precipitation. This suggests that the temperature changes (negative) are having a more pronounced change on SWE than increases in precipitation. The decreases in SWE were found to be most pronounced within low elevation basins. As a result of warming trends and lower volumes of snow pack, peak runoff rates from snowmelt have begun to trend earlier in the year.

Knowles et al., (2006) closely evaluated the trend toward earlier runoff by comparing the SWE to winter-total precipitation for the western United States. They found that there is a trend toward smaller SWE compared to winter-total precipitation. This means more precipitation is occurring in the form of rain instead of snow.

Kalra et. al., (2007) evaluated April 1 SWE data from 121 SNOTEL stations from 1941 to 2004 in the western United States. After stations exhibiting significant autocorrelation were excluded, SWE observations at the remaining SNOTEL sites showed decreases from 1941 to 2004.

U.5.1.3 Streamflow Trends

Streamflow patterns in the western U.S. are significantly affected by snowmelt conditions, motivating interest in comparing streamflow and SWE trends. Streamflow is of primary concern in water management, as reduced streamflow can negatively impact reservoir operations. Decreasing streamflow can have an adverse effect on hydroelectric power generation, irrigation demands, recreational activities, and the environment (e.g., Regonda et. al., 2005). The timing of peak streamflow is also of concern, as changes to the timing of peak streamflow may affect flood control, impact the environment, and impose hardship on those dependent on the timing of flow due to seasonal snowmelt, such as farmers. Investigation of streamflow records typically uses observations from the United States Geological Survey (USGS), specifically from gages within the Hydro-Climatic Data Network (HCDN), which are USGS streamgages minimally affected by anthropogenic regulation and with a sufficient period of record.

Kalra et al., (2007) examined long-term trends and abrupt step changes within the USGS HCDN data over various basins and time scales (i.e., water year, seasonal, and decadal). No significant trends in streamflow volumes were found for the Colorado River basin over the entire length of record. These results are also confirmed from prior studies (e.g., Lins and Slack, 1999; Groisman et al., 2001; McCabe and Wolock, 2002; Pagano and Garen, 2005; Stewart et al., 2005). The tendency for no trend in total annual streamflow is reasonable considering that there is no trend in total annual precipitation. However, the tendencies in changes in seasonal streamflow volumes may be more apparent due to the expected changes in temperature (warmer) and the form of precipitation in warmer future climate scenarios.

U.5.2 Future Climate

The future water supply for the Colorado River basin will depend on many climatic factors. Climate change may alter the quantity and timing of local and regional precipitation. Higher temperatures would mean more precipitation falling as rain than snow, reducing snowpack water storage, likely greater evaporative losses, and shift in the timing of runoff to be earlier in the season. While it is difficult to make certain predictions of changes in the overall quantity of precipitation for the region, scientific theory suggests that higher carbon dioxide (CO_2) concentrations warm the lower atmosphere, raising its water holding capacity, which, among other things, intensifies the global hydrological cycle (Meehl, et al. 2005; Trenberth et al. 2003). In some regions, this could lead to more intense but possibly less frequent periods of precipitation. In other words, we may see longer periods of drought, alternating with spells of heavy snowfall and rainfall events, and subsequent changes in the timing and magnitude of runoff. Such changes could create a number of difficulties for water managers throughout the Colorado River basin. For example, greater runoff variability could make it more difficult to maintain optimal reservoir levels, which could reduce the reliability of water storage, although this is less a problem in the Lower Colorado than elsewhere due to the size of overyear storage.

U.5.2.1 Global Climate Change

The scientific evidence for human-caused global climate change has become quite compelling in recent years. The Intergovernmental Panel on Climatic Change (IPCC) recently released the first of four parts of its Fourth Assessment Report (AR4 IPCC 2007), describing the science and physical evidence surrounding climate change. This also includes the anticipated changes in water resources summarized by the Working Group II in "The Summary for Policymakers." The consensus among involved scientists and policy makers is that "… global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750… and the understanding of anthropogenic warming and cooling influences on climate leads to *very high confidence* that the globally averaged net effect of human activities since 1750 has been one of warming.. ." Certainly, other forcings act on the climate system beyond human influences, most notably solar, volcanic, oceanic, and cryogenic (ice) forcings, but when these processes are included alongside human forcing, an anthropogenic "fingerprint" emerges.

CO_2 is a major green house gas, contributing somewhere between 10 and 25 percent of the natural warming effect, second only to water vapor. As the earth emits long wave radiation toward space, atmospheric constituents like water vapor, CO_2, ozone, and methane absorb this energy flow and radiate energy back to earth. Climate models suggest that without these greenhouse gases the average earth temperature would be about 19ºC cooler, and in the absence of other changes and feedbacks in the climate system, a doubling of CO_2 would warm the lower atmosphere by about 1.2ºC (Kiehl and Trenberth 1997).

Figure U-4 is a plot of annual mean departures from the 1961-90 average for global temperatures (with a mean of 14.0°C) and carbon dioxide concentrations from ice cores and Mauna Loa (1958 on), with a mean of 333.7 ppmv (updated from Karl and Trenberth 2003). The plots show that the rise in CO_2 coincides with a rise in global average surface temperatures.

Increasing CO_2 is not the only human activity affecting our climate system and in fact, CO_2 is only responsible for about two-thirds of the greenhouse effect, the rest being attributable to methane, nitrous oxide, chlorofluorocarbons, and ozone. Changes in land use, aerosol emissions from fossil fuel burning, the storage and use of water for agriculture, etc. are all environmental changes that affect climate (Pielke et al., 2007). Climatologists have tried to quantify the relative role of various human factors on the climate system in terms of each component's "radiative forcing", which are summarized in Figure U-5 and taken from the AR4. Most notably, the radiative forcing of CO_2 is the largest single component, with natural solar irradiance (solar variability) substantially smaller. Also, there are human activities that counteract the positive forcing of CO_2. For examples, aerosols from the burning of fossil fuels tend to reflect heat back into space, reducing the net heat at the surface. When all the components are considered, there is a net positive radiative forcing on the order of 1.5 watts per square meter (W/m^2).

Figure U-4
Global average temperature and CO_2 trends (Karl and Trenberth 2003)

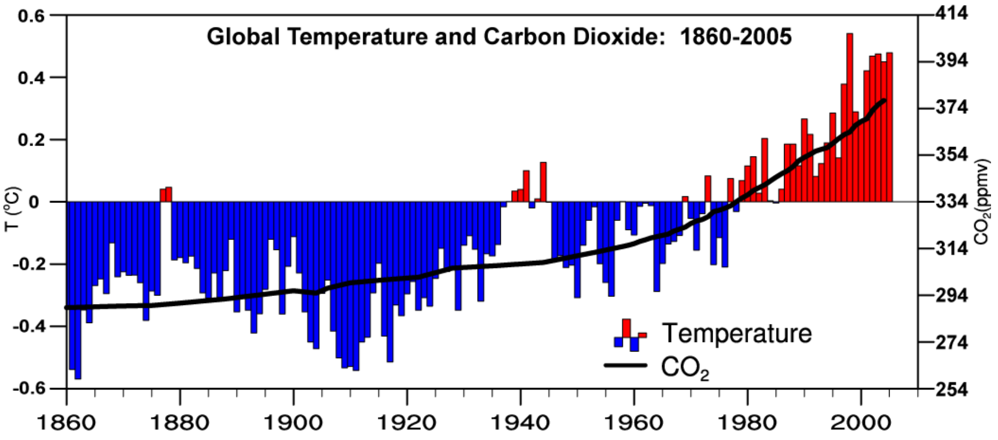
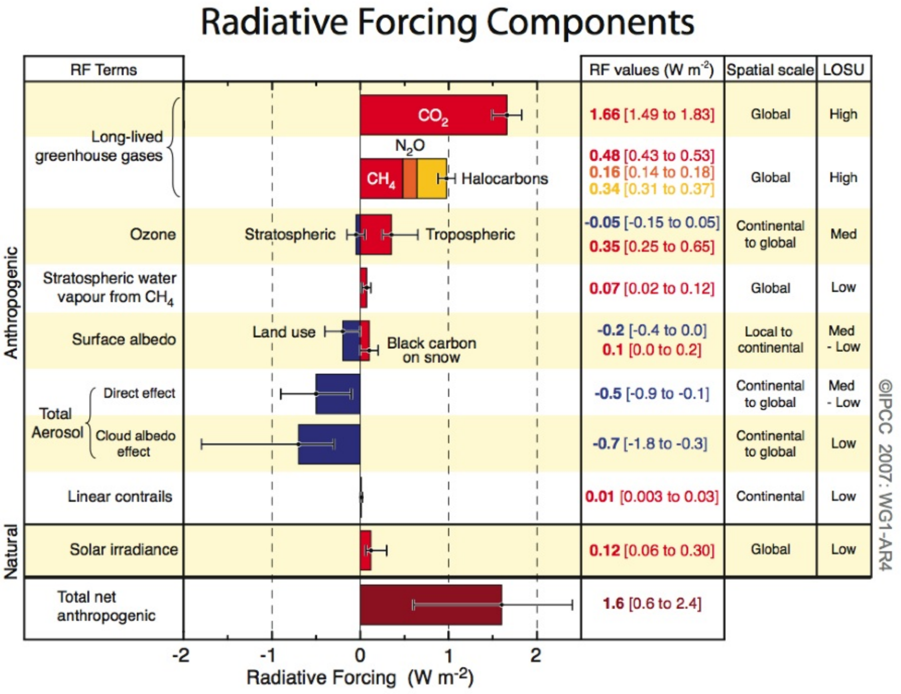


Figure U-5
Relative Radiative Forcing Attributable to Human Activities,
Where “Positive” Means that the Earth is Gaining Energy Faster Than It is Losing It
(RF-Radiative Forcing; LOSU- Level of Scientific Understanding)

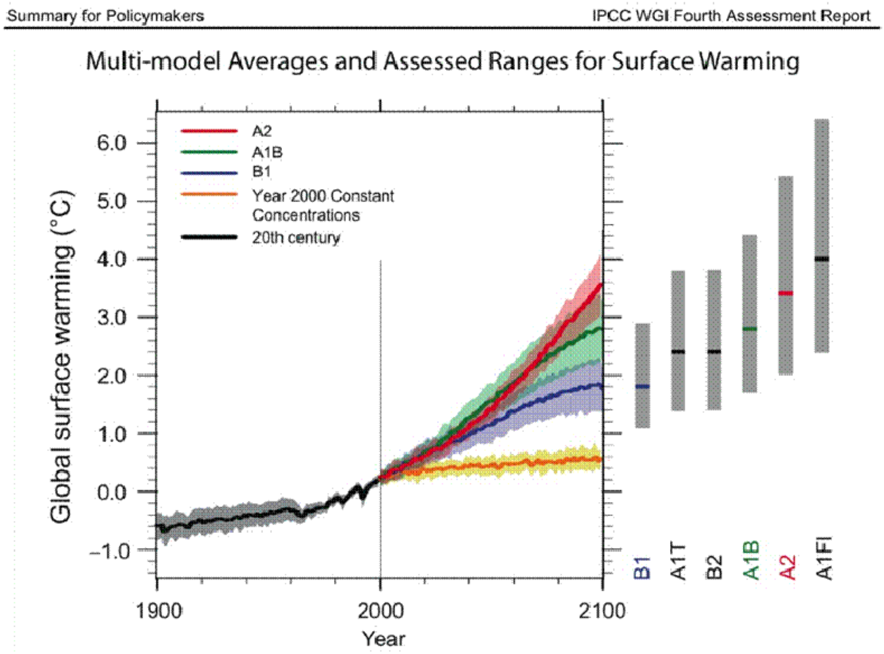


Problematically, CO_2 has a relatively long residence time in the atmosphere and while its sources are local, it is generally globally distributed. Recognizing that it is a strong forcing component, the IPCC has convened panels of experts that have developed "storylines of the future", which are used to project concentrations of greenhouse gases. These transient concentrations are then used in Generalized Circulation Models (GCMs) to project the relative contribution of CO_2 (and other factors) to future warming. Most GCMs consist of an atmospheric module that is coupled to the other key components of the climate system, including representation of oceans, sea ice, and the land surface. The major GCMs include tens of vertical layers in the atmosphere and the oceans, dynamic sea-ice sub-models and effects of changes in vegetation and other land surface characteristics (Washington, 1996; Gates et al., 1999). The atmospheric part of a climate model is a mathematical representation of the behavior of the atmosphere based upon the fundamental, non-linear equations of classical physics. A three-dimensional horizontal and vertical grid structure is used to track the movement of air parcels and the exchange of energy and moisture between parcels.

The CO_2 storylines include both "green" centered trajectories that moderate fossil fuel use and fossil fuel intensive trajectories, leading to either low or high green house gas concentrations, respectively. These different emission pathways then imply different mean global and regional climate warming rates. The details of these scenarios are beyond the scope of this report, but Figure U-6 summarizes the projected global average surface warming based on a consensus derived from several GCMs across a range of future projections (e.g. referred to 'A2', 'A1B', and 'B1' scenarios; for details about the different scenarios, see http://www.ipcc.ch/pub/sres-e.pdf). Note this figure includes a projected global average temperature if we were to keep CO_2 at 2000 concentration levels, suggesting that we are already *committed* to further warming beyond anything that has taken place already.

The consequences of the projected future warming are likely to be changes in atmospheric and oceanic circulation, and in the hydrologic cycle, leading to altered patterns of precipitation and runoff. Scientists agree on some of the important broad-scale features of the expected hydrologic changes, the most likely of which will be an increase in global average precipitation and evaporation as a direct consequence of warmer temperatures. That, however, does not mean that there will be more precipitation everywhere or that runoff and recharge would increase in proportion to precipitation.

Figure U-6
From the IPCC Working Group I, Fourth Assessment Report, Summary for Policy Makers (IPCC 2007)

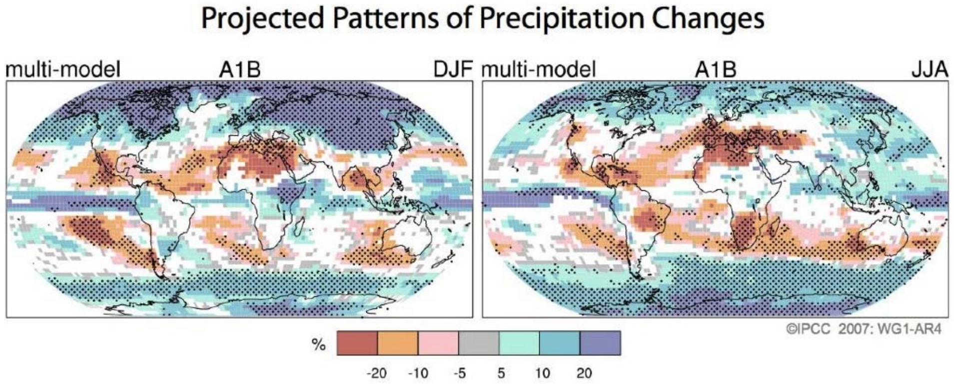


Historic observed global average temperatures, and projected global average temperatures based on various projections of global CO_2 concentrations.

U.5.2.2 Regional Climate Change

At the regional scale, such as the Colorado River basin, there is high confidence in projections of future temperature change, with less confidence in projections of future precipitation change (Dai, 2006). Changes in circulation patterns will be critically important in determining changes in precipitation and water availability, and climate models can provide only a crude picture of how those patterns may change. The currently available evidence suggests that arctic and equatorial regions may become wetter, and that subtropical regions may experience drying. Projections of precipitation changes for mid-latitude regions such as the Colorado River basin are less consistent, but generally indicate a drier climate (e.g., Milly et al., 2005; Seager, 2007). Seager (2007) argues for an imminent transition to a drier climate in southwestern North America. He points out the consistency of climate models in producing a human-induced aridification caused by large scale changes in the atmospheric branch of the hydrological cycle, stating that “the subtropics are already dry because the mean flow of the atmosphere moves moisture out of these regions whereas the deep tropics and the higher latitudes are wet because the atmosphere converges moisture into those regions. As air warms it can hold more moisture and this existing pattern of the divergence and convergence of water vapor by the atmospheric flow intensifies. This makes dry areas drier and wet areas wetter.” Figure U-7 shows projected patterns of precipitation change. Note the general pattern of drier conditions in the mid-latitudes and desert regions, and wetting in the tropics and high latitudes (IPCC 2007).

Figure U-7
Statistical Summary of Projected Patterns of Precipitation Change from Multiple
General Circulation Models for December, January and February (left) and June, July, and August (right)

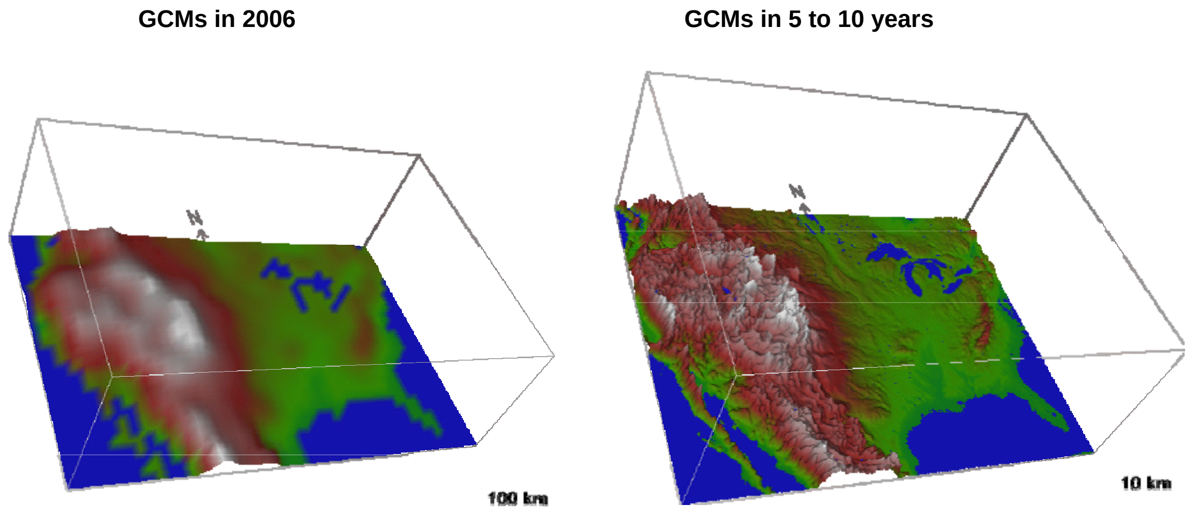


The stippled areas show region where there is greater agreement among models.

However, climate simulations of southwestern North America are problematic because the region is both downstream from the Pacific and also in an area where topography can make a difference, issues that are not well captured in the bulk of GCMs (if correct in any at all). The climate of the Southwestern US depends greatly on the dynamics in the tropical and extra-tropical Pacific Ocean circulations that are not accurately simulated in current GCMs. The subtle dynamics of the jet stream and storm tracks particularly in the winter and the influence of the North American Monsoon in the summer are also important and not well represented. Despite tremendous technological advances in computing capability, it is still very time consuming and costly to use these models to simulate future climates. One of the most important compromises for achieving model results in a reasonable amount of time is to decrease the model's horizontal resolution. This limitation means that it is prohibitively costly to run a GCM at a spatial resolution that would accurately depict the effects of mountains and other complex surface features on regional climates.

The problem with such a coarse horizontal resolution is that important processes occurring at finer scales are not well resolved (Figure U-8). Topography, for example, is very important in determining the location of precipitation. As moist air rises over mountains or hills, the moisture condenses, producing clouds and, if conditions are right, precipitation. Although there has been marked improvement over the last three decades in the simulation of precipitation, it is still not well represented in GCMs, especially in areas of complex topographies, since the coarse horizontal resolution of GCMs tends to smooth out important landscape features that affect atmospheric processes. At the resolution of most GCMs the models represent the mountains of the western United States as a set of gentle ridges and do not resolve finer scale features that influence regional climate. Clearly, that level of spatial resolution is too coarse to reproduce the effects of topography on the region's precipitation and runoff patterns (Grotch and MacCracken, 1991; Giorgi and Mearns, 1991; Pan et al. 2004).

Figure U-8
Horizontal Spatial Resolution Depicted by Typical
Global Climate Models, and Where We Hope to Be in the Next 5 to 10 Years



The current inadequacies of GCMs and the recognition that each has its own strengths and weaknesses has led researchers to conclude that no single model can be considered ‘best’ and it is important to utilize results from a range of coupled models for regional impact and adaptation studies (Allen et al., 2000). Tebaldi et al., (2006) presented a probabilistic approach that combines the regional output of 21 unique GCMs to produce probabilistic projections of regional, future climate change. Their statistical model combines information from each GCM, including each model’s ability to re-create the regional climate over the period 1960 through 1990 (a measure of a model’s bias), and the agreement among models in future projections. Models that diverge greatly from other models are given less weight in deriving the final statistical distributions of change. Figures U-9 a and b show probabilistic projections of future seasonal temperature and precipitation change in the Upper Colorado River basin for the 2000-2020 and 2040-2060 period for the low CO_2 emission, B1 scenario; the “middle-of-the-road” A1B emissions scenarios; and the high A1 emissions scenario for the Upper Colorado River basin.

Not surprising, the projection differences among the three scenarios from 2000 to 2020 are not substantial since the CO_2 trajectories are very similar in the early period, with regional mean warming just below 1ºC. It isn’t until later in the 21st century, that the projections diverge under the various CO_2 scenarios. The Tebaldi et al., (2006) results suggest a GCM model consensus of temperature increases a bit below 1ºC over the next 20 years, with some seasonal variation. Interestingly, the results show moderate increases in winter precipitation across all scenarios, with little or no change in spring and fall precipitation and slight decreases in summer precipitation, with some scenario dependency (bottom, Figure U-9 b). By the 2040 to 2060 period, the mean regional warming projections exceed 1ºC and the magnitude of the regional temperature increases are much more tied to the specific projection scenario. Remarkably, the temperature projections for the moderate (A1B) and higher emissions scenario (A2) are quite similar, while the precipitation projections show slightly wetter winters under the moderate B1 scenarios and slight *drying* over these decades for the higher A1B and A2 higher CO_2 projection scenarios. All three scenarios show summer drying and little or no change in the spring and fall “shoulder” seasons.

Figure U-9 (a)
Scenario-specific Absolute Change in Temperature (top) and Percent Change in Precipitation (bottom) in the Upper Colorado for the Period 2000-2020
DJF, MAM, JJA, SON for the B1, A1B and A2 Scenarios

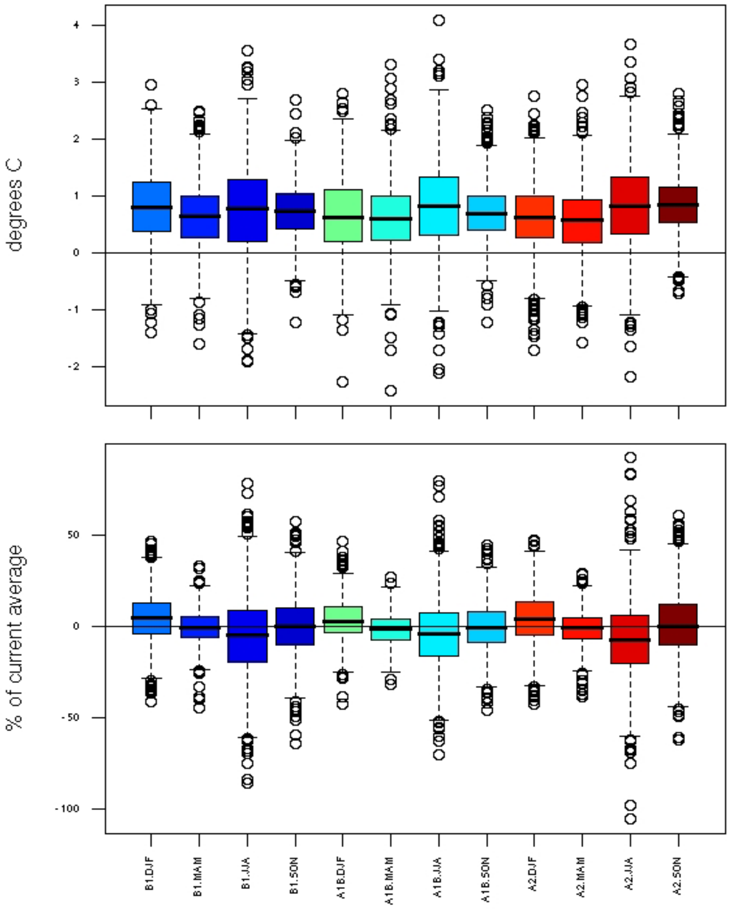
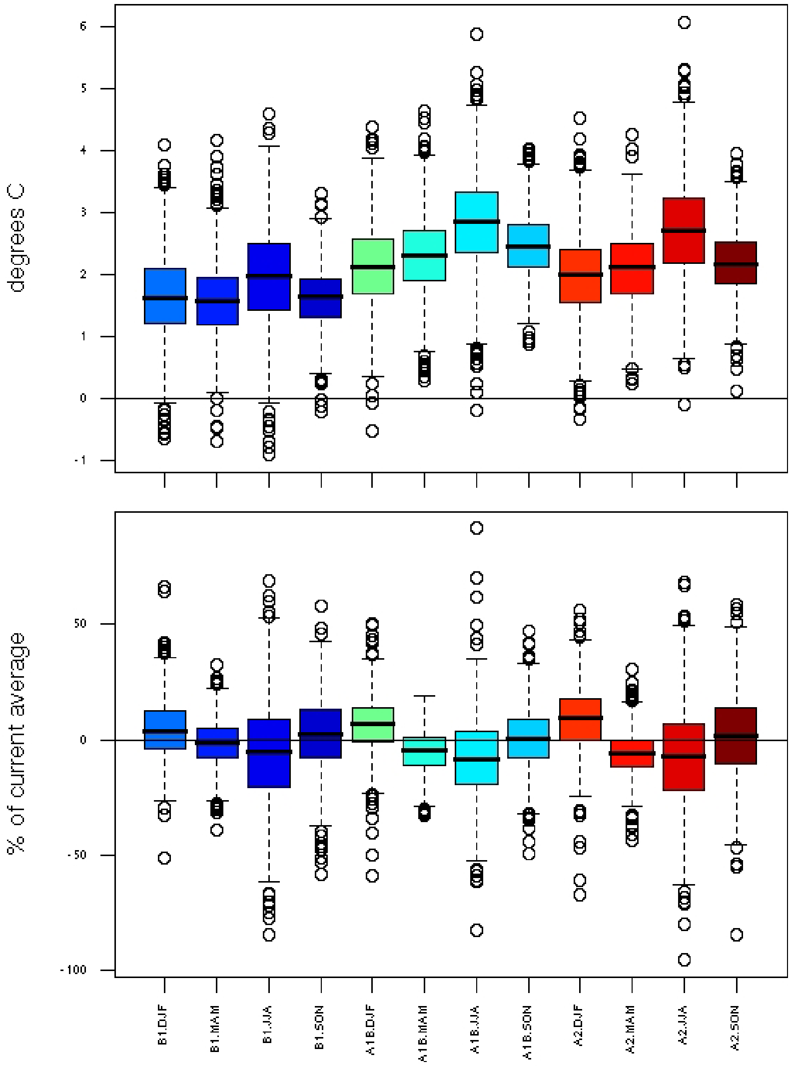


Figure U-9(b)
Scenario-specific Absolute Change in Temperature (top) and
Percent Change in Precipitation (bottom) in the Upper Colorado for the Period 2040-2060
DJF, MAM, JJA, SON for the B1, A1B and A2 Scenarios



GCMs also produce runoff estimates that can be useful in identifying whether regions are going to have more or less water resources. Milly et al., (2005) evaluated the global patterns of water availability under climate change scenarios. Depending on the region of the globe, annual runoff could increase or decrease. The relative changes for the southwest U.S. were decreases in annual runoff. These estimates are for large areas and downscaling is necessary to identify regional impacts. This is discussed further in Section U.4.2.3.

U.5.2.3 Regionalizing Future Climate Projections (Downscaling)

As was summarized in previous sections, GCMs are able to simulate large-scale climate features realistically, but exhibit biases at a regional scale. The regional biases are problematic for analysis of climate implications for hydrology and water resources (Maurer, 2007). Recognizing the regional limitations of GCMs has led to the application of "downscaling" as a means of trying to understand how local scale processes, of greater interest to water resource planners, might respond to larger-scale weather and climate changes (Wilby et al., 2004). Regardless of the technical approach, the primary goal is to process the raw GCM output so that it reflects the large-scale features and temporal trends from the GCM simulation, but also the historical patterns of climate variables at the regional and local scale (Wood et al., 2004).

Downscaling techniques generally fall into classes involving either simulated (dynamical), statistical, or bias-correction/disaggregation methods. Downscaling can produce more sub-regional detail and eliminate system biases between observed local climate and climate generated by GCMs. Downscaling does not necessarily provide more reliable information or increase our confidence in a particular GCM scenario for climate change. Several downscaling approaches are summarized:

Dynamic Methods. This class involves the use of regional climate models run at a relatively high resolution over a limited area with boundary conditions (and sometimes interior domain information as well) prescribed from the lower resolution GCM. This is often referred to as "dynamical" downscaling since the regional climate model explicitly accounts for the dynamic aspects of the climate system that operate on finer spatial scales than the GCM can represent. It is possible for these "nested models" to resolve some limitations of general circulation models for a specific region. They are still limited in their capabilities to give reliable projections for future precipitation change. The intensive computational demands of dynamical models severely limit their usefulness for producing long-range climate change scenarios. Proponents argue, however, that mesoscale models uniquely represent important feedback mechanisms (such as the effects of land surface albedo on boundary layer climate dynamics) that may moderate or enhance climate change.

Statistical and Bias Correction Methods. This class of downscaling methods involves deriving statistical relationships between observed small-scale (often station level) variables and larger (GCM) scale variables, using analogue methods (circulation typing), regression analysis, or neural network methods (Mearns, 1999; Yates et al., 2003, Clark and Hay, 2004). Future values of the large scale variables obtained from GCM projections of future climate are then used to drive the statistical relationships and estimate the smaller-scale details of future climate.

Stochastic weather generators have been used to develop climate datasets for impact analysis. These can address some of the issues just raised with their ability to simulate plausible climate scenarios, and have themselves been used as downscaling techniques in global change studies (Wilks, 1992). Typically, a stochastic weather generator is developed based on the historically observed data at a location, and can then be used to simulate climate scenarios consistent with the global change scenarios. However, Katz

(1996) points out that modifying the parameters of a stochastic model can lead to unanticipated effects. For example, modifying the probability of daily precipitation occurrence using a stochastic weather generator (Richardson 1981) also changes the mean and standard deviation of the daily temperature as well.

The statistical downscaling approach of Maurer (2007) and Wood et al., (2002; 2004) is relevant because it was used in recent studies of the Colorado River basin (Christensen and Lettenmaier, 2006); Christensen et al., 2004). The method involves two steps: (a) identifying and accounting for bias between GCM-simulated climate variables and corresponding observations during a "common historical overlap period", and (b) disaggregating the bias-corrected GCM output to region and local scales so that the information is more spatially consistent with the basin and local scales considered in impacts analyses. The procedure improves upon an earlier downscaling techniques (called the "perturbation" method) that involved identifying and applying adjustment factors based only on climatological monthly mean differences in observed precipitation (P) and temperature (T) and between GCM output and observations (e.g., Lettenmaier et al., 1999; Miller et al., 2003). The limitations of such an approach are that it doesn't consider GCM interannual variability, does not address the GCM's potential bias in temporal variability, and can result in implausible precipitation sequences after rescaling. Recently, techniques address these limitations through the use of distribution-mapping between GCM gridded output and historical gridded observations (Maurer, 2007; Wood et al., 2002).

Implementation of the latter bias-correction technique requires definition of "observed historical" using a reference gridded climate dataset (e.g., usage of National Climate Data Center Cooperative Observer Data aggregated to 2° latitude-longitude spatial resolution). The "common historical overlap period" is then defined, where both "observed historical" data and GCM historical simulation data are considered. Within this historical period, month-specific cumulative distribution functions (CDFs) are calculated, describing the range and distribution of P and T conditions at each grid point in the region of consideration. (Note: GCM historical simulation data may have to be interpolated and mapped to grid point locations consistent with the observed dataset's grid or vice versa) Bias-correction within the "common historical overlap period" then ensues: on a grid-point by grid-point basis, the quantiles for GCM-simulated P and T CDFs are then mapped to the same quantiles for the observationally based CDF at a grid-point by grid-point basis. For example, suppose the 70th percentile GCM P value for December is adjusted to equal the 70th percentile observed P value for December. This basis for adjusting GCM output is then carried forward beyond the "common historical overlap period" to adjust GCM-projected conditions. For example, let's say a projected December P value happens to equal the median unadjusted GCM-historical December P value. Just as the GCM-historical median value was adjusted to equal the observed median value, the projected value would be adjusted in the same fashion. For GCM T values, the full-period linear trend in the simulation is removed prior to bias-correction, and then replaced afterwards (Wood et al. 2004; Maurer 2007).

Following bias-correction, the GCM gridded dataset is spatially disaggregated, or "downscaled", to a finer resolution. While other dynamical or statistical methods could be used at this stage, a relatively simpler interpolation technique has been used in recent applications (Wood et al., 2002; Wood et al., 2004; Maurer et al., 2007; Christensen and Lettenmaier, 2006).

Relative Limitations Among Method. Each technique has strengths and weaknesses. For example, simulated downscaling would seem to offer the best capability in preserving physical relations between local- and larger-scale climate features, even under a changing climate. That said, the simulation approach is computationally intensive and constrains consideration of multiple climate change scenarios and future periods to be considerably less than what might be considered using statistical or bias-correction/disaggregation methods. Likewise, the latter two methods are computationally efficient, but relatively more limited in how they approximate the relation between local- and larger-scale climate features. Statistical methods assume a stationary relationship that may not hold under a changing climate. Disaggregation rests on the assumption that the variance of conditions simulated in a GCM should be constrained by the variance of observed climate conditions, even though such an assumption might not hold true as climate changes.

Substituting Sensitivity Analysis for Downscaling-Analog Methods. Conducting downscaled analyses based on the projections from multiple climate models can be a very laborious and time-consuming task. The daunting prospect of developing detailed climate data sets for impact analysis has led to simpler "scenario" approaches in contrast to the "projection" based approach which rely on GCM results and the downscaling steps just described.

The scenario approach includes simple "back-of-the-envelope" methods that can explore the possible implications of climate change for water resources. Since it is unlikely that we will be able to "predict" the climate of the future, we can be informed by the climate of the past and at least be guided or bound by the projected future changes. For example, what are the consequences throughout the basin of a reoccurring 1930's 'dust-bowl' era drought, with current population and water use, and what if a 1ºC warming were superimposed on top of these conditions? This approach introduces a "worst case" climate scenarios on a regional or local scale based on historical events, such as a region's most severe drought in the past century or climate traces developed from tree ring studies. This approach has the advantage of realism, because events that occurred in the past could occur again. A drawback of this approach is that the hypothetical scenarios may not be internally consistent and it is difficult to estimate their likelihood. Despite those drawbacks, systematic analysis of such scenarios can be useful for delineating the relative importance of changes in temperature and precipitation and can provide an inexpensive way to explore vulnerabilities of water supply systems, water quality, and in-stream resources.

Several analyses have used hypothetical changes in temperature and precipitation amounts by simply scaling a historic record by some predefined amount, essentially amounting to a sensitivity analysis to a climate perturbation. Such a climate scenario would simply take historical climate sequences and add an absolute temperature change and/or a percent change in precipitation to this historical record, with the magnitudes of changes bounded by the regional changes suggested by GCMs. If climate models suggest a 1ºC warming over the next 30 years, then a 30 year, 1ºC trend can simply be added to the historic temperature data. This kind of sensitivity analysis is useful for understanding the response of the hydrologic system to a warmer climate.

U.6 A Review of Assessments of Climate Change Impacts in the Colorado River Basin

Section W.5.1 in this chapter provides an overview of the six major studies since 1979 on how climate change might affect the runoff of the Colorado River. Section W.5.2 discusses more general recent studies on potential hydrological changes in the American Southwest under a warmer climate including the new IPCC regional findings. The final section summarizes and discusses all of the studies including limitations and the range of future projections.

U.6.1 Literature Review of Colorado River Climate Change Studies

Since 1979 there have been six major studies on how climate change might affect runoff in the Colorado River (See Table U-2). These studies approach the problem using two, or in some cases three steps. The first step is to obtain future temperature and precipitation by using either arbitrary scenarios or GCM outputs. Early studies used the former approach while more recent studies have used the latter technique. The second step is to use the temperature and precipitation and possibly other climatic variables in either statistical/empirical relationships or hydrology models to generate streamflow. Finally, some of the studies use an ‘operational’ model to convert projected streamflows into reservoir levels, compact deliveries, energy production, and other information. These steps are depicted in Figure U-14 for one of the studies. In addition to the major studies on the basin, there have been several other smaller studies and these are discussed at the end of this section.

U.6.1.1 Geohydrological Implications of Climate Change on Water Resource Development (Stockton and Boggess, 1979)

Charles Stockton[1], of the University of Arizona Laboratory of Tree-Ring Research, and William Boggess wrote a report prepared for the U.S. Army Corps of Engineers Engineering Research Center in 1979. The authors investigated how four different climate change scenarios would impact the water supplies of the United States.

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[1] Stockton was also coauthor of the 1976 Stockton and Jacoby Colorado River tree-ring reconstruction discussed in 7.1

Table U-2
Summary of Model Results for Colorado River Basin

Study	Flow Generation Technique	Selected Results on Typical Changes in Flow (doesn't reflect range of change across studied scenarios)	Notes
Stockton and Boggess, 1979	Langbein's 1949 US Historical Runoff-Temperature-Precipitation Relationships	+2C and -10% Precip = ~ -33% reduction in Lees Ferry Flow	Results are similar for the warmer/drier and warmer/wetter scenarios. Cooler and wetter and cooler and drier are very likely not applicable.
Revelle and Waggoner, 1983	Regression of runoff on Upper Basin Historical Temperature and Precipitation	+2C and -10% Precip= -40% reduction in Lee Ferry Flow	+2C only = -29% runoff, -10% Precip only = -11% runoff. Regression can be used to calculate a variety of projections.
Nash and Gleick, 1991 and 1993	NWSRFS Hydrology model runoff derived from 5 temperature & precipitation Scenarios and 3 GCMs using doubled CO_2 equilibrium runs.	+2C and -10% Precip = ~ -20% reduction in Lee Ferry Flow	Many runoff results from different scenarios and sub-basins ranging from decreases of 33% to increases of 19%. Used USBR CRSS Model for operations impacts
Christensen et al., 2004	UW VIC Hydrology model runoff derived from temperature & precipitation from NCAR GCM using Business as Usual Emissions.	+2C and -3% Precip at 2100 = -17% reduction in total basin runoff by 2100	Used single GCM with low temperature sensitivity to CO_2 increases. Created and used operations model, CRRM.
Hoerling and Eischeid, 2006	Regression of runoff on PDSI developed from 18 AR4 GCMs and 42 runs using Business as Usual Emissions.	+2.8C and ~0% Precip = -45% reduction in Lee Ferry Flow by 2035-2060	Range of results is considerable. Reduction in runoff seen even when using 20th century historical wet period with 21st century projected temperatures.
Christensen and Lettenmaier, 2006	UW VIC Hydrology Model runoff using temperature & precipitation from 11 AR4 GCMs with 2 Emissions scenarios.	+4.4C and -2% Precip at 2070-2099 = -11% reduction in total basin runoff by 2070-2099	Range of results is considerable including some with increased runoff, especially in earlier 21st century periods. Increased winter precipitation apparently buffers reduction in runoff. Also used CRRM operations model.

The scenarios were the four combinations of +/- 2ºC along with +/- 10% change in precipitation, and were generically called *warmer and drier, cooler and wetter, cooler and drier, and warmer and wetter*. At the time of this report there was some discussion about the possibility of a new ice age, (global temperature records indicated a cooling from 1940 to 1970) yet the National Academy of Sciences issued a prescient report about the potential for global warming, Carbon Dioxide and Climate: A Scientific Assessment, (Charney, 1979) that same year. Hence, the study considered all possible future climates.

In all parts of the country except the Upper Colorado basin, they determined that scenarios 1, (*warmer and drier*), and scenario 2 (*cooler and wetter*) set the lower and upper bounds on runoff changes since changes in temperature and precipitation in the *cooler and drier* and *warmer and wetter* scenarios usually offset each other. In the Upper Colorado River the warmer and wetter scenario also showed substantial decreased runoff.

Stockton and Boggess utilized relationships developed by Walter Langbein (Langbein, 1949) of the USGS in the 1940s showing how precipitation and temperature jointly affect runoff across the United States. Langbein's nomograph (Figure U-10) shows that for the *same precipitation* runoff decreases as temperature increases, and for the *same temperature* runoff increases as precipitation increases, with runoff increasing faster when precipitation is high.

For the Upper Colorado River, Stockton and Boggess calculated that runoff would decrease by about one-third to approximately 10 maf under the *warmer and drier*, and, surprisingly, under the *warmer and wetter* scenarios. Under *cooler and wetter*, annual flow doubled to 30 maf, while under the *cooler and drier* scenario runoff was effectively unchanged.

Figure U-10
Nomograph of Relationship Between Mean Annual Precipitation (inches), Mean Annual Temperature (ºF) and Mean Annual Runoff (inches) in the United States (from Langbein, 1949)

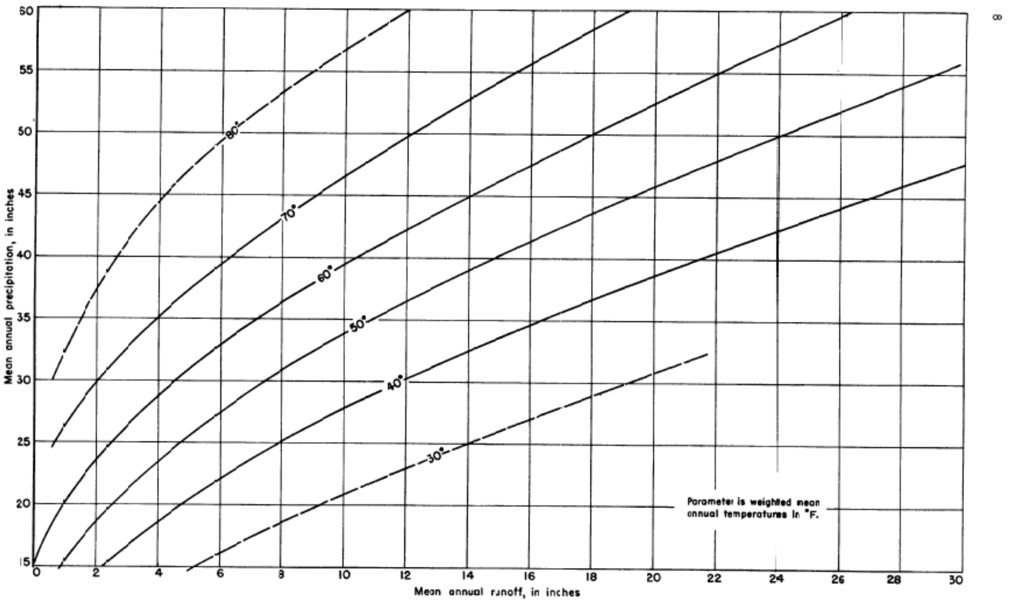

Figure 2.--Relationship of annual runoff to precipitation and temperature.

Data appropriate to Colorado River is in lower left-hand corner.

U.6.1.2 Effects of a Carbon Dioxide-induced Climatic Change on Water Supplies in the Western United States (Revelle and Waggoner, 1983)

In 1983 Roger Revelle, of the Scripps Institution of Oceanography, and Paul Waggoner, of the Connecticut Agricultural Experiment Station, wrote a chapter in *Changing Climate, Report of the Carbon Dioxide Assessment Committee*, published by the National Academy of Sciences. The authors investigated how future warming and drying in the Colorado River might affect runoff. The first part of the article restated in tabular format the empirical relationships established by Langbein in 1949 (Table U-3) among temperature, precipitation and runoff for arid areas.

Table U-3
Revelle and Waggoner's Restatement of Langbein's Relationship
Between Temperature, Precipitation and Runoff

Precip in inches (") →									
Temp (ºC)	Temp (ºF)	8"	%P as runoff	12"	%P as runoff	16"	%P as runoff	20"	%P as runoff
-2	28.4.	2.1	27%	3.6	31%	6.1	39%	9.1	46%
0	32	1.3	20%	2.9	25%	4.9	31%	7.5	38%
2	35.6	1.1	14%	2.2	19%	3.7	24%	6.1	31%
4	39.2	0.7	8%	1.6	13%	3.1	20%	4.9	25%
6	42.8	0.4	4%	1.0	8%	2.4	15%	3.9	20%
8	46.4	0.0	0%	0.7	6%	1.7	11%	3.2	16%
10	50			0.3	3%	1.1	7%	2.5	13%
12	53.6			0.0	0%	0.7	5%	1.9	9%
14	57.2					0.4	3%	1.3	6%
16	60.8					0.0	0%	0.8	4%

Shaded area represents the runoff portion roughly applicable to the Upper Colorado River Basin – Revelle and Wagonner's 1931-1976 data indicated the Upper Basin average temperature was 40F/4C with about 330mm/12" of precipitation.

The second part reviewed the 1979 findings of Stockton and Boggess, discussed above. The third and most frequently cited part of the article generated a multiple linear regression between Upper Basin temperature and precipitation, and unimpaired flow at Lee Ferry. Using the period 1931 to 1976 they established the following relationship:

Lee Ferry Annual Flows (in maf) = 42.1 + 1.07*(Annual Precipitation in inches)
-1.08*(Annual Average Temperature in Fahrenheit)[2]

The equation explains 73% of the variance in flows (r2=.73) and shows that a 2ºC/3.6ºF increase (1931-1976 Upper basin average was 4.18ºC/7.5ºF) would lead to a decline in runoff of by 4800 mcm (3.9 maf) or 29% and a 10% decrease in precipitation (1931-1976 basin average was 333 mm/13.1") would reduce flow by 1730 mcm (1.4 maf) or 11%. With both a 2ºC increase and 10% precipitation decrease, flow would decline by 40%. They note that the regression shows that a 28% increase in precipitation is necessary to balance a 2ºC increase.

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[2] The original version was in metric units: Lee Ferry Annual Flows (in cubic meters) = 9274 + 52(Annual Precipitation in mm) -2400(Annual Average Temp in Celsius)

Figure U-11
Scatterplot Showing the 1931-1976 Precipitation and Flow Data
Used by Revelle and Waggoner (1983)

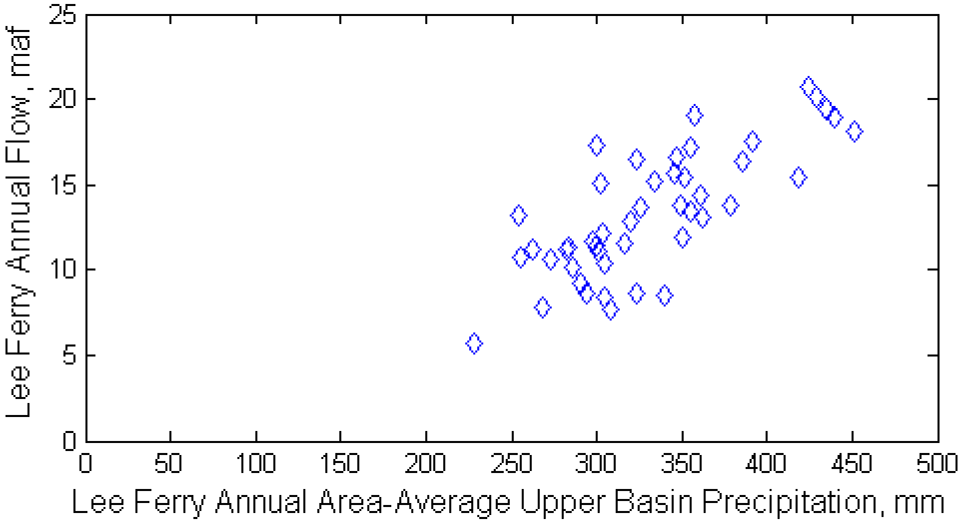
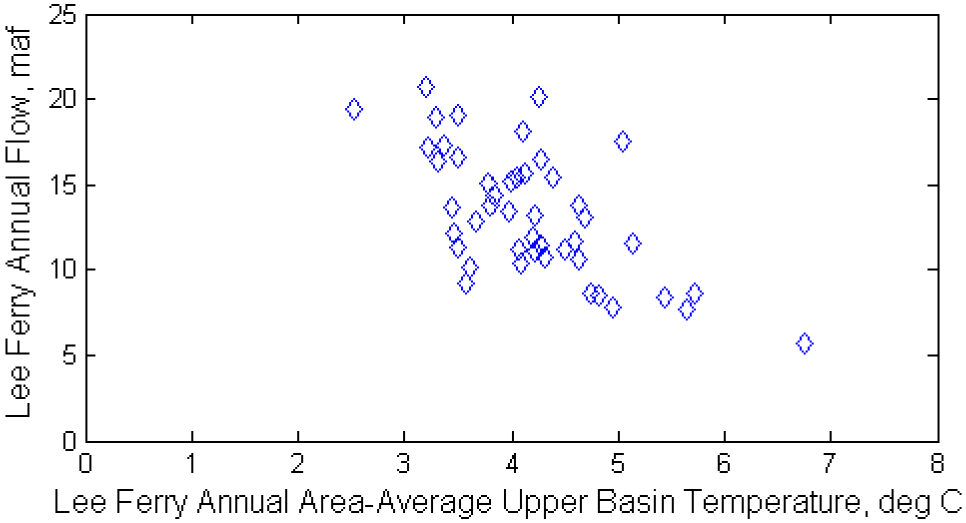
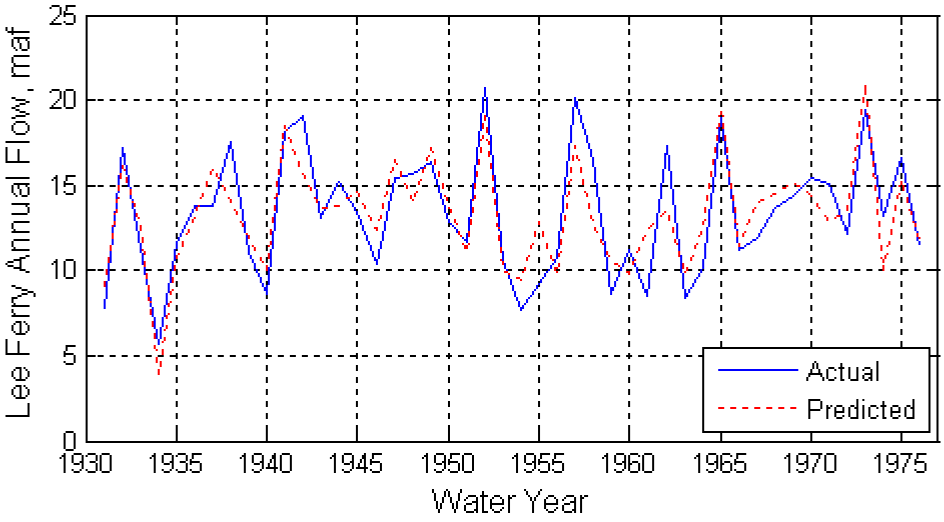


Figure U-12
Scatterplot Showing the 1931-1976 Temperature and Flow Data
Used by Revelle and Waggoner (1983)



Revelle and Waggoner also constructed a regression (not provided) using data from 1901 to 1930 but this only explained 57% of the variance. The authors felt the relatively low explained variance was due to a limited number of data stations, a lack of snoU-related precipitation data, and stations unrepresentative of true temperatures.

Figure U-13
Actual and Predicted Flows Using Revelle and Waggoner
(1983) Regression Equation



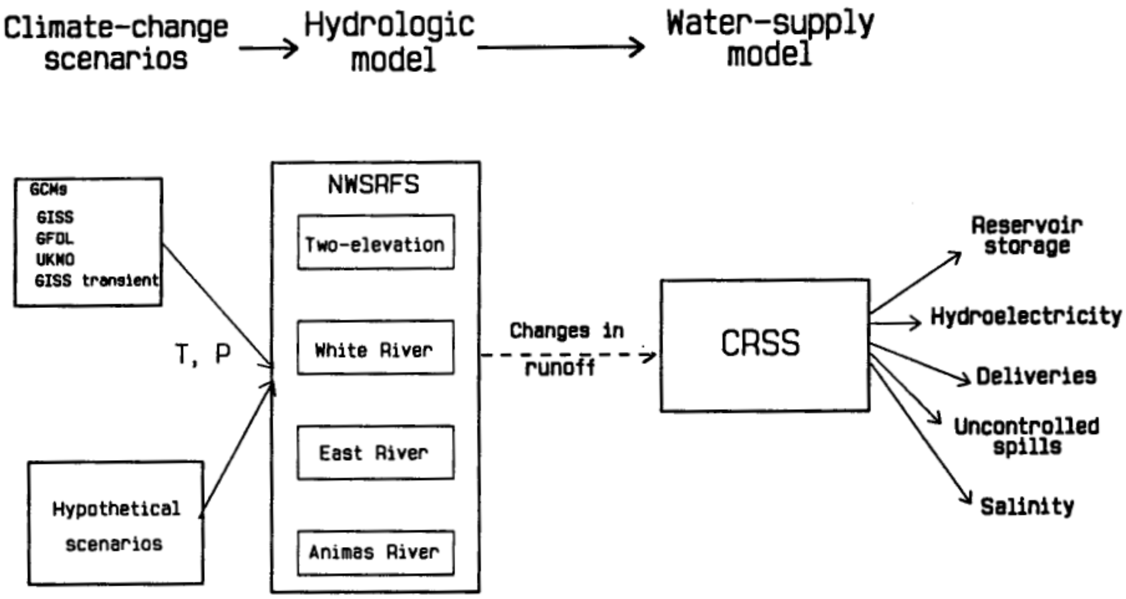
U.6.1.3 *Sensitivity of Streamflow in the Colorado River basin to Climatic Changes (Nash and Gleick, 1991) and The Colorado River basin and Climatic Change (Nash and Gleick, 1993)*

Linda Nash and Peter Gleick of the Pacific Institute for Studies in Development, Environment and Security wrote two similar articles on future Colorado River flows under varying assumptions of a changing climate, one published in the Journal of Hydrology (Nash and Gleick, 1991) and one as a report to the Environmental Protection Agency as part of a grant (Nash and Gleick, 1993). The 1993 article is an expanded version of the 1991 study and includes the addition of results of modeling simulated future flows with Reclamation's CRSS River operation model (See Figure U-14).

In the Nash and Gleick (1991) study, the authors considered a total of 15 different scenarios for temperature and precipitation conditions, 10 from assumed futures and five based on GCM simulations. These scenarios were then used as meteorological inputs into the National Weather Service River Forecasting System (NWSRFS) hydrologic model in three relatively unimpaired sub-basins of the Colorado River basin above Lake Powell. NWSRFS is the operational model used by the NOAA National Weather Service Colorado River basin River Forecast Center (CBRFC) and all other River Forecast Centers. It is composed of the Sacramento soil moisture model and the Snow17 snowmelt model, among other components.

The NWSRFS applications had been previously calibrated by CBRFC staff and had r2 values between historical and forecasted flows of approximately 0.9 on a monthly basis. Mean streamflow predictions were biased by about +/-1% relative to historical flows. (The authors noted that the NWS used entire historical data set in calibration thereby making it impossible to use some of this data in independent model verification studies.) This study simulated future streamflow in three of the sub-basins in the NWSFRS model with limited human influences, the White River near Meeker, the Animas River near Durango, and the East River near Gunnison. In addition, inflows were simulated for Lake Powell by using a coarser two-elevation aggregated model.

Figure U-14
Drawing from Nash and Gleick, 1993, Showing the Different Models Used in the Study



Sources of different temperature and precipitation inputs used to drive the hydrologic model are on the left. The Christensen studies have a similar hierarchy, but utilize different models at all three points.

The hypothetical scenarios involved all combinations of 2ºC and 4ºC temperature increases, and changes in precipitation of -20%, -10%, 0%, +10% and +20%. The GCM-based efforts used GCM temperature and precipitation outputs from the nearest grid point or grid points in two cases. GCM ouput data were taken from two Goddard Institute for Space Studies model grid points (+4.8ºC /+ 20% precipitation and +4.9ºC/+10% precipitation), a NOAA Geophysical Fluid Dynamics Laboratory model (+4.7ºC / 0% precipitation), and two UK Meteorological Office model (UKMO) grid points (+6.8ºC/+30% precipitation, and 6.9ºC/+10% precipitation)[3]. The GCM outputs were

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[3] The versions of the GISS, GFDL, and the UKMO GCMs used in the recent 2007 IPCC AR4 studies are vastly different from those used in Nash and Gleick (1991, 1993).

derived from a doubled-CO_2 experiment where CO_2 concentrations were instantly doubled and then the GCMs were allowed to achieve temperature equilibrium.

Fifty-two (52) different scenarios were evaluated (not every modeled flow point used every scenario.) Thirty-seven (71%) scenarios resulted in flow decreases and fifteen (29%) resulted in flow increases. Runoff varied from a 33% decrease to a 19% increase. A 20% increase in precipitation caused runoff to increase in every case. A 2ºC increase was roughly offset by a 10% increase in precipitation. A 2ºC increase with no change in precipitation caused runoff declines of -4% to -12%. A 4ºC increase with no change in precipitation caused runoff declines from -9% to -21%. A 4ºC increase must be matched with precipitation increases of +15% to +20% for runoff to stay constant. The aggregated two-elevation model for Lake Powell inflow was more sensitive to increases in temperature than the other models, either an artifact of the model or a physical manifestation of increased evaporation in the lower elevation zones of this modeled runoff point compared to the relatively high elevations at the other modeled points. The results follow expectations with higher temperatures and lower precipitation generating less runoff. Temperature increases also cause the peak flow to shift earlier in the year.

In the 1993 study Nash and Gleick added (1) a "transient" climate study showing results for the decade 2030 to 2039, (2) a direct GCM runoff analysis (runoff calculated by the GCM as part of its hydrology code, not the runoff from the NWSRFS), and (3) an operations model, CRSS, to investigate how changes in inflows would affect reservoir operations and system reliability. Transient climate studies use fully specified month by month GHG emissions scenarios that generally increase over time as inputs and keep continuous daily, monthly or annual output data from the GCM for later analysis, rather than just the final equilibrium response. All current studies such as the Christensen et al. (2004), Christensen and Lettenmaier (2006) and Hoerling and Eischeid (2006) are based on models which have archived transient climate output.

This was the first Colorado River study to find that chronic small reductions in streamflow are ultimately manifested as large declines in system storage and hydropower due to total demands that are at or near the mean streamflow. Many other studies such as the Severe and Sustained Drought study (Harding et al., 1995), Christensen et al., (2004), and Christensen and Lettenmaier (2006) have confirmed these findings.

In the 1993 study, runoff reductions of 20% caused mean annual reductions in storage of 60 to 70% and reductions in power generation of 60%. A 15% drop in runoff caused Lee Ferry minimum flows to drop by 86%. A 10% runoff reduction caused Lake Powell releases to fall below the 8.23maf target in several years and storage to decline by 30% relative to historical levels. The specific results from this study are very dependent on assumptions made about how to allocate shortages, reservoir starting conditions, Upper Basin compact deliveries during extended drought, and other factors.

U.6.1.4 The Effects of Climate Change on the Hydrology and Water Resources of the Colorado River basin (Christensen, et al., 2004)

This 2004 study, published in a special edition of the journal Climatic Change, was part of a larger study funded by the Department of Energy known as the Accelerated Climate Prediction Initiative (ACPI). Niklas Christensen, Andrew Wood, Nathalie Voisin, Dennis Lettenmaier and Richard Palmer, all of the Department of Civil and Environmental Engineering at the University of Washington, used the National Center for Atmospheric Research Parallel Climate Model (PCM) to simulate runoff and operations on the Colorado River during three future 21st century periods, 2010-2039, 2040-2069, and 2070-2098 (See Table U-4).

The version of PCM in the study featured coupled atmospheric, ocean, sea ice and land surface components and operated at T42 resolution or approximately 300km grid boxes. At the time, PCM simulations showed less cooling (‘temperature sensitivity’) than many other GCMs for the same greenhouse gas emissions. This version of PCM was part of the multi-model ensemble referenced in IPCC’s Third Assessment Report (2001) and contrasts with the version of PCM and other models that are referenced in IPCC’s Fourth Assessment Report results shown in Section W.4.0.

Table U-4
Changes in Temperature and Precipitation Provided by NCAR GCM, Runoff and Snow Water Equivalent Results from VIC Hydrology Model, and Storage, Hydropower and Spills from CRRM Operations Model
(from Christensen et al., 2004)

Period	Temperature (ºC)	Precipitation	Runoff	Snow Water Equivalent	Storage
Historical Control	0.5	354 mm/yr	45 mm/yr		32.3 MAF/yr
		-1%	-10%		-7%
2010-39	1.0	-3%	-14%	-2%	-36%
2040-39	1.7	-6%	-18%	-7%	-32%
2070-39	2.0	-3%	-17%	-8%	-40%

Monthly temperature and precipitation output from PCM was downscaled to 1/8 degree daily data (see Section W.4.2.3.2) for use by a daily hydrological simulation model, the Variable Infiltration Capacity (VIC) model. VIC simulates snow accumulation and melt, soil moisture, evapotranspiration, and runoff and baseflow. Runoff and baseflow are routed through a flow network so that streamflow can be calculated. VIC was calibrated using climate and natural flow data from 1950 to 1989. Calibration runs indicated a flow match at Imperial Dam within 1% of calculated natural flow at the site. At Cisco near the Colorado-Utah state line, VIC flow was 9% smaller than calculated natural flow, and at Green River, Utah, VIC was 3% larger than calculated natural flow. VIC output was used in a monthly operations model, Colorado River Reservoir Model (CRRM), based roughly on Reclamation’s CRSS model.

Three future PCM runs for the 21st century were used. (These "ensemble members" were created by initializing PCM with slightly different atmospheric conditions.) A 50-year control climate run starting in 1995 with no additional greenhouse gas emissions (i.e., with fixed 1995 GHG levels) was also completed. PCM 21st century results averaged over the three runs were compared to the control run, and to historical observed data or calculated natural flow in the historical period.

Due to lags in the climate system, the control run showed warming of about 0.5ºC which is in rough agreement with what many believe to be 'committed warming' should greenhouse gas emissions stop immediately. The three 21st century runs showed average increases of approximately 3ºC over the observed average temperature of 10ºC. In general the warming was concentrated in spring and summer.

Average annual precipitation in the control run was 1% less than historical, and in the three 21st century runs was 3%, 6%, and 3% lower in Periods 1, 2, and 3 respectively. The seasonal precipitation pattern in the control run was very similar to the historical observed, and the 21st century runs showed a similar pattern but with less precipitation in the spring.

April 1 snow water equivalent (SWE) in the control run was only 86% of the observed historical SWE, while SWE was 76%, 71%, and 70% in Periods 1-3, respectively. The reduction in SWE in the control run was attributed to higher spring temperatures, and the 21st century reductions were due to higher temperatures and/or reduced winter and spring precipitation. Southern Colorado suffered the highest reductions and those occurred in Periods 2 and 3.

Runoff was reduced by 10% in the control run, and by 14%, 18% and 17% in periods 1-3, respectively, in the 21st century runs. A spatial analysis of these reductions indicated that a considerable enhancement of evapotranspiration increases occurred in the high elevation areas where a large portion of runoff occurs. Peak runoff advanced from June in the historical data to May in the latter parts of the control and 21st century runs.

Christensen et al., (2004) also reported extensively on how these flows would affect operations as modeled in CRRM. The authors caution that these results strongly depend on initial conditions in the operations model and should not be interpreted as predictions but used instead to find system sensitivities to changes in future flows. Most of the modeling was predicated on constant year 2000 Upper Basin demands to simplify analysis, but a set of runs were done with Upper Basin demands increasing over time.

As previously reported by Nash and Gleick (1993), the authors found that because the Colorado River is nearly at full allocation, reservoir reliability and storage levels were extremely sensitive to inflow reductions -- average reservoir levels dropped significantly even with small reductions in runoff. For example, storage in the control run dropped by 7%, and periods 1-3 showed reductions of 36%, 32%, and 40%, respectively, relative to simulated historical conditions. Deliveries from Lake Powell were met 92% of the time in the historical data, and 72% in the control run and 59%, 73%, and 77% in periods 1-3, respectively. The control run showed reductions relative to the historic conditions because it used year 2000 demands. Variability in the 21st century runs explains some of the other differences. For example, a wet period at the end of Period 2 left system reservoirs at a relatively high level and hence reliability in Period 3 was slightly higher than Period 2 despite roughly similar SWE and runoff.

U.6.1.5 Past Peak Water in the Southwest (Hoerling and Eischeid, 2006)

Martin Hoerling and Jon Eischeid of the NOAA Earth System Research Laboratory in Boulder published their findings in December of 2006 in Southwest Hydrology, a magazine (not a peer-reviewed journal) that is part of the National Science Foundation funded effort at the University of Arizona known as Sustainability of Semi-arid Hydrology and Riparian Areas (SAHRA). Hoerling and Eischeid (2006) projected future Colorado River flows based on the Palmer Drought Severity Index (PDSI) calculated from modeled climate changes for the Upper Colorado River basin. PDSI is a frequently used drought metric and is calculated by combining temperature, precipitation, evapotranspiration and soil moisture. The index can vary from -4 (extreme drought) to +4 (extreme wetness).

Using historical data from 1895 to 1989, they first created a simple linear regression for the Upper Colorado basin:

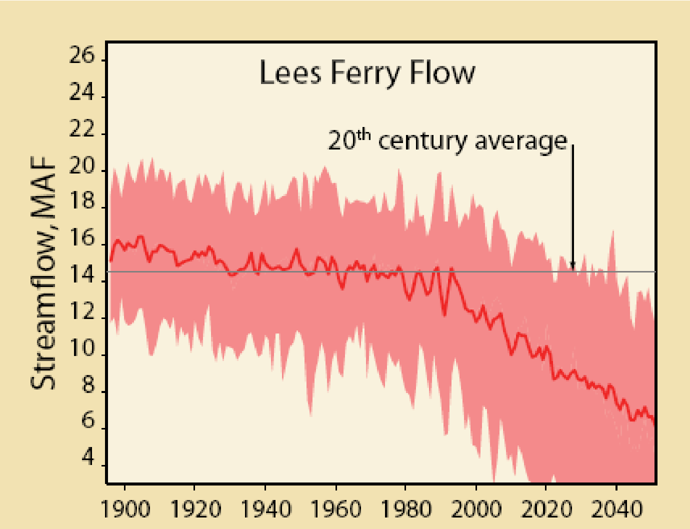
$$\text{Lee Ferry Annual Flows (in MAF)} = 14.5 + 1.69(\text{PDSI})$$

This regression explains 63% of the variance at Lees Ferry over the 105-year calibration period. The equation explained 85% of the variance in the flows over a verification period from 1990 to 2005.

Hoerling and Eischeid then proceeded to calculate the future PDSI using temperature and precipitation data from 42 different climate simulations using ‘business as usual’ greenhouse gas emissions (A1B) from 18 different coupled atmosphere-land-ocean models completed for the recent IPCC 4th Assessment. They then used the regression model above to translate these PDSI values into projected future annual streamflow (See Figure U-15).

The authors found that annual streamflows in the river over the next twenty-five years would average 10 maf, approximately the same as during the recent 1999-2004 drought. From 2035 to 2060 the flows would drop to an average of 7 maf. The individual years vary considerably from these averages with some years being close to the historical mean of 15 maf (see figure). For the next twenty years, individual years may still produce normal flows. In some future years the regression equation did generate some streamflows below zero (not shown). Although negative flows are obviously physically impossible, this is a known limitation when regression equations are used outside of their calibration inputs.

Figure U-15
Projected Lees Ferry Future Flows



Solid line is average of 42 runs, and shaded band shows 10% to 90% range of individual simulations
(from Hoerling and Eischeid, 2006)

The authors noted that the climate models show little net change in precipitation over the next century yet significant drought as represented by the modeled PDSI would be a very common occurrence with average PDSI the same as during the 2000-2003 drought (<-3). They suggested that 20th century droughts were driven by precipitation decreases with enhancement by temperatures but a "near perpetual state of drought will materialize in the coming decades as a consequence of increasing temperature." The models in the study project an average temperature increase of 1.4ºC during 2006-2030, and average warming of 2.8ºC during 2035-2060, compared to 1895-2005.

The authors cautioned that it is unclear if the streamflow PDSI relationship used in the study is strictly applicable to the substantial changes anticipated in future climate. It should also be noted that the PDSI index was developed for use in the Great Plains and does not account for the different phases of precipitation, snow or rain, and their very different characteristics.

U.6.1.6 A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River basin (Christensen and Lettenmaier, 2006)

Niklas Christensen and Dennis Lettenmaier, both with the Department of Civil and Environmental Engineering at the University of Washington published in an article on future Colorado River flows in *Hydrology and Earth System Sciences* in 2006. The study is based on GCM model results prepared for the 2007 IPCC Fourth Assessment (AR4) (see Table U-5 for rounded temperature, precipitation, runoff and snow water equivalent results; and, Figures U-15 to U-18 for additional information on this study).

The authors used 11 major climate models and two different future emissions scenarios, A2, a relatively high scenario with 2100 CO_2 levels of 850 ppm and B1, a relatively low level scenario with 2100 CO_2 levels of 550 ppm. (Current CO_2 levels are approximately 380 ppm and are increasing at about 1.5 – 2.0 ppm/year.) The authors selected these two scenarios because they likely bracket any future emissions trajectory and because the GCM output for these scenarios was available from a wide variety of models.

This study essentially reapplied the approach from the Christensen et al. 2004 Climatic Change paper but featured an expanded suite of climate models. As in the 2004 study, for discussion the output was broken into 3 periods: 2010-2039, 2040-2069, and 2070-2099.

Table U-5
Average Ensemble Temperature Increase, Percent Changes in Precipitation, Runoff, and April 1 Snow Water Equivalent All Relative to Historic 1950-99 Modeled Base Case for Both the B1 and A2 Emissions Scenarios
(from Christensen and Lettenmaier, 2006)

Period	Temperature (ºC)		Precipitation		Runoff		Snow Water Equivalent	
	B1	A2	B1	A2	B1	A2	B1	A2
2010-39	1.3	1.2	1%	-1%	0%	0%	-15%	-13%
2040-69	2.1	2.6	-1%	-2%	-7%	-6%	-25%	-21%
2070-99	2.7	4.4	-1%	-2%	-8%	-11%	-29%	-38%

For this study VIC was re-calibrated on historic 1950-99 data (an additional 10 years relative to the 2004 study). VIC generated a less than 1% underprediction of streamflow at Imperial Dam, and +3% and -9% errors at Green River and Cisco, respectively, based on reconstructed natural flow at these points.

Temperatures increases (ºC) for the B1 runs during periods 1-3, shown as "average (minimum, maximum)," were 1.28 (0.53, 1.83), 2.05 (1.13, 2.99), and 2.74 (1.13, 2.99), respectively, relative to historical observations (see Table U-5 for rounded temperature, precipitation, runoff and snow water equivalent results. Figures U-15 to U-18 present additional information on this study). For the A2 runs during the same periods, the temperature increases (ºC) by 1.23 (0.63, 1.82), 2.56 (1.61, 3.65), and 4.35 (2.77, 6.06). (Many studies show that temperatures in the next quarter century are tied to existing greenhouse gas concentrations and hence the slightly higher B1 temperature relative to A2 in period 1 is not unusual; generally, changes between emission scenarios show lagged behavior such as reported for Periods 2 and 3.) Temperature increases show more warming from mid-summer to early fall, which is consistent with a reduction in soil moisture during these periods.

Annual precipitation percent change from historical for the B1 runs during periods 1-3, shown as "average (minimum, maximum)," were +1% (-8, 11), -1% (-11, 9), -1% (-11, 19), respectively. For the A2 runs and same periods, percent precipitation changes were -1% (-9, 7), -2% (-21, 13) and -2% (-16, 13), respectively. Of critical importance is that October to March average precipitation increases by +5%, +1%, and +2% for B1 and by

+6%, +5% and +4% for the A2 scenario. In contrast, the 2004 study had winter precipitation decreases in the single digits. The increases occurred generally at the highest elevations in the Rockies.

April 1 snow water equivalent (SWE) change from historical for the B1 runs, shown as “average (minimum, maximum),” was -15% (-41, 0), -25% (-48, -1), -29% (-53, -18) during for periods 1-3, respectively. For the A2 runs, SWE change was -13% (-36, 1), -21% (-52, 6) and -38% (-66, -15) during the same periods, respectively. The authors believe that SWE decreases are due to increasing temperatures, given especially that winter precipitation increases. SWE reductions are greatest in the low to mid elevation areas. The combination of declining SWE and increasing winter precipitation is indicative of more precipitation occurring as rain.

Mean-annual runoff during Periods 1-3 changed from historical by 0% (-23, 17), -7% (-27, 12) and -8% (-30, 29) for the B1 runs, respectively, and by 0% (-16, 14), -6% (-39, 18), and -11% (-37, 11) for the A2 runs during the same periods. These reductions are larger than the precipitation declines and are believed to be driven by increasing temperatures and high evapotranspiration.

Christensen and Lettenmaier (2006) also reported results from their operations model, CRRM. CRRM was modified to reflect the Basin States’ current proposal with regard to how Lower Basin shortages should be tied to Lake Mead Levels. Hence, the model calculates shortages when necessary to all major Lower Basin entities. They caution that CRRM results reflect many assumptions and non-linear interactions, such as reservoir initial starting conditions and the sequencing of individual annual inflows. In addition, as previously stated, all Colorado River operations models including CRRM fail to address certain critical issues including, for example, Upper Basin curtailments as may be required by the Colorado River Compact during extended drought. Upper Basin demands were fixed at year 2000 levels to simplify analysis yet over time these demands will surely grow. Thus these results should be used only in a comparative sense.

In general, CRRM reservoir levels are higher than reported in the 2004 study, although the authors claim that the results are within the same range of sensitivity. They state that a decrease of 10% in average streamflow is magnified into a 20% change of the same sign in reservoir storage. Similarly, a 20% inflow change results in a 40% storage impact. The authors state that because of the large ratio of storage to inflow in the basin, neither increases in storage nor changes in operating rules will likely change the storage impacts under declining inflows.

U.6.1.7 Other Colorado River Basin Studies of Note

In addition to the studies reported above, there have been several other studies, either focused on parts of the basin or that summarize past studies. These are discussed briefly below.

In 1990 John Schaake of NOAA’s Office of Hydrologic Development investigated the notion of elasticity in flow due to changes in precipitation and temperature in a chapter entitled “From Climate to Flow” in *Climate Change and U.S. Water Resources* (Schaake

1990). Using the NWSRFS hydrologic model on the Animas River basin, Schaake discovered that a 10% increase in precipitation would increase flow by 20% while a 2°C temperature increase would reduce flow by 2%. A 2°C increase and a 10% increase in potential evapotranspiration would change flows by -9%.

Greg McCabe and Lauren Hay of the USGS wrote Hydrological Effects of Hypothetical Climate Change in The East River Basin, Colorado, USA in Hydrological Sciences in 1995 (McCabe and Hay, 1995). McCabe and Hay used 9 hypothetical climate scenarios – all combinations of +4°C, 0C, -4C and -20%, 0%, and +20% precipitation – to drive a USGS hydrologic model, PRMS. Modeled runoff varied from -30% (+4C, -20%) to +40% (-4C,+20%). The authors also investigated how natural variability might mask decreasing runoff and found that it might take 80 to 90 years to detect a runoff reduction at the 95% confidence level due to a gradual +4C and -20% precipitation change.

In 1999 in the Journal of the American Water Resources Association, Peter Gleick and Elizabeth Chalecki wrote The Impacts of Climatic Changes for Water Resources of the Colorado and Sacramento-San Joaquin Basins (Gleick and Chalecki, 1999). This article provides an overview of all studies on the Colorado River prior to the publication date.

U.6.2 Recent Studies Featuring GCM Projections for the American Southwest

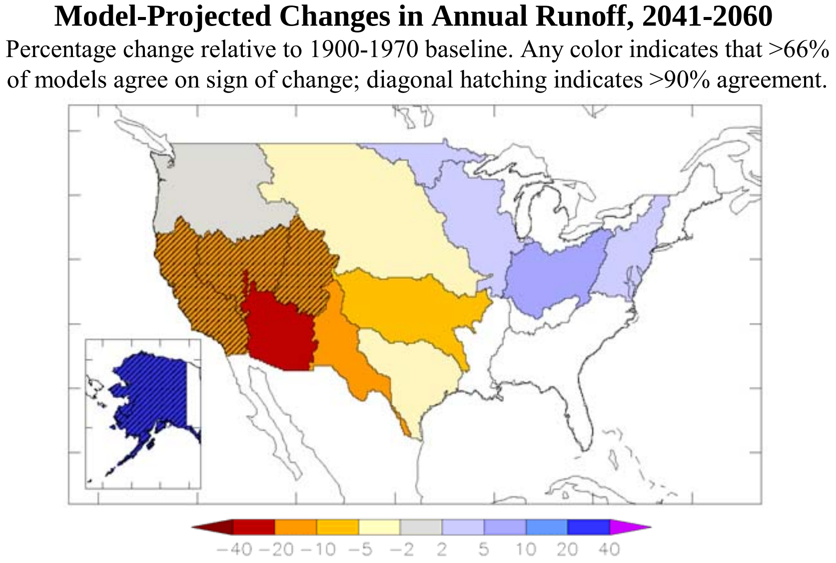
Since 2005 there have been three studies which have analyzed large scale 21st century GCM projections such as runoff, precipitation and evaporation for the American Southwest. These studies have not utilized smaller scale hydrologic or other models like the studies described in Section W.5.1. An important distinction between studies using GCM runoff versus hydrology model runoff is that whereas GCMs calculate runoff as part of their hydrological cycle at the GCM scale (e.g., for 10,000 km^2 grid cells), hydrological models like VIC and NWSRFS run at much higher resolution, contain far more detailed representations of land surface physics, and are calibrated and verified against streamflow records, which is not typically the case for runoff from GCM internal runoff schemes.

U.6.2.1 Global pattern of trends in streamflow and water availability in a changing climate (Milly et al., 2005)

In the journal Nature in 2005, USGS scientist Chris Milly and others surveyed runoff proxy information from 12 AR4 GCMs found to be relatively better skilled at reproducing 20th century streamflow trends over large regions. The study had both a 'verification' period which used historical data to select the 12 models from 21 potential candidates, and a projection period using SRES A1B which used future runoff from the selected models. The American Southwest was not one of the areas used to select the models and hence model fidelity to historical conditions in this region is not known. The runoff projections were for the entire globe. In a later not-published addendum to the study, Milly looked specifically at the continental United States and found that based on the same model results greater than 90% of the GCM simulations show future Colorado

River basin runoff reductions from approximately 10 to 30% (see Figure U-16) in the period 2041-2060[4].

Figure U-16
Projected Colorado River Runoff (from Milly et al., 2005)



Model-Projected Changes in Annual Runoff, 2041-2060

Percentage change relative to 1900-1970 baseline. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement.

(After Milly, P.C.D., K.A. Dunne, A.V. Vecchia, Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, **438**, 347-350, 2005.)

The IPCC AR4 Working Group 1 chapter on climate models (Randall et al., 2007) as well as the AR4 Working Group 2 chapter on freshwater resources (Kundzewicz et al., 2007) both relied on this study. Randall et al. noted that this study was an important scientific advance because it showed that despite the limitations in the hydrologic cycle in the climate models, the models can capture observed changes in 20th century streamflow associated with atmospheric conditions. Further, they say that, "This enhances confidence in the use of these models for future projection."

U.6.2.2 Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, (Seager et al., 2007)

A 2007 study in Science by Columbia University scientist Richard Seager and others, using many of the same GCMs and runoff proxy information as Milly et al., obtained similar conclusions to Milly et al. Unlike Milly et al.'s world-wide focus, Seager's study was specific to an area he termed the 'American Southwest' but was actually far larger than the general use of this term[5]. This area includes the entire Lower Basin, but excludes

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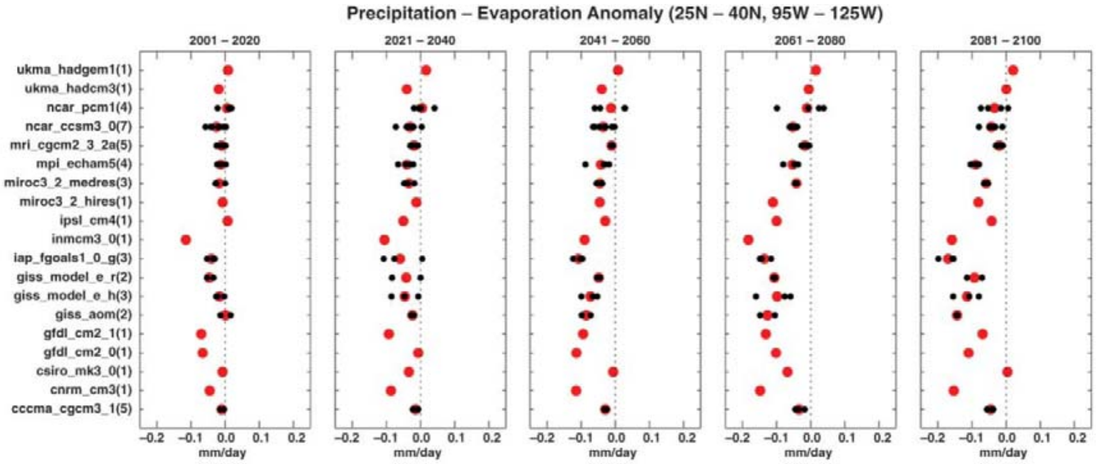
[4] Enhanced Graphics of the U.S. from the addendum are available at: http://www.gfdl.noaa.gov/~pcm/project/runoff_change.ppt and these graphics are shown below.

[5] The area was all land from 125U-95W and 24-40N or approximately Brownsville, TX to Lincoln, NE to Eureka, CA in the U.S. It also includes land in Mexico.

almost all of the Green River and hence is not equivalent to the Colorado River basin. Seager et al. used future GCM projections from 19 AR4 climate models using the A1B emissions scenario compared to 1950-2000 model climatologies. Eighteen of the nineteen models show a drying trend (see figure U-17). Seager et al., focus on the change in future precipitation less future evaporation, a proxy for runoff. In support of the modeled runoff declines, Seager et al., (2007) point to theory and studies about Hadley cell expansion and associated poleward storm track movement in a warming climate. They also discuss recent observational and paleoclimate evidence for support of hypothesized Hadley cell changes.

Figure U-17
The Change in Annual Mean Precipitation Minus Evaporation (~ Runoff) for the
American Southwest in Twenty-Year Periods to 2100 Calculated Relative to Model Climatologies 1950-2000



Models are shown at left. Red dots are the ensemble mean and black dots represent individual ensemble members. Only 1 in 19 models has a wet trend and only 3 individual projections out of 49 show a wet trend. (from Seager et al., 2007)

U.6.2.3 Intergovernmental Panel on Climate Change, 2007

The Fourth Assessment of the Intergovernmental Panel on Climate Change released its report in the spring of 2007 (IPCC, 2007). Chapter 11 from The Physical Science Basis Work Group contains regional climate projections, including North America (Christensen et al., 2007). Christensen et al[6]., note that for North America as a whole, the annual mean warming is likely to exceed the global mean warming in most areas. Snow season length and snow depth are very likely to decrease in most of North America, except in the northernmost part of Canada where maximum snow depth is likely to increase. At the coarse horizontal resolution of the climate models, high-altitude terrain is poorly resolved, which likely results in an underestimation of warming associated with snoU-albedo feedback at high elevations in western regions.

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[6] This is not the same Christensen as in the Christensen and Lettenmaier studies.

Specific IPCC findings for the Southwestern USA are that warming will likely be greatest in summer, not winter as for other parts of the continent, and that annual mean precipitation is likely to decrease (see Figure U-7). The projection of smaller warming over the Pacific Ocean than over the continent, and amplification and northward displacement of the subtropical anticyclone, is likely to induce a decrease in annual precipitation in the south-western USA and northern Mexico. In the context of the report, 'likely' is used to mean a 66% to 90% chance of occurrence. Regional projections are only made for relatively large areas without definite boundaries such as the "Southwestern USA". The IPCC makes regional projections where there is "near unanimity among models with good supporting physical insights." They note that up-to-date coordinated Regional Climate model projections were not available for North America at the time the report was issued.

U.6.3 Synthesis and Discussion of Results

Almost thirty years have passed since the first attempt by Stockton and Boggess (1979) to quantify how climate change might affect the runoff in the Colorado River basin. Since that early attempt using Langbein's 1949 empirical temperature-precipitation-runoff relationships, scientists have used primarily two types of future climate temperature and precipitation projections– (1) pure hypothetical scenarios and (2) GCM output – to drive two types of flow generation techniques – (1) statistical regression and (2) hydrology process models – in order to project future flows on the river. To put these studies into proper context it is important to understand the limitations relating to GCMs, future applicability of statistical and empirical relationships based on historical data, hydrology model assumptions, and/or operational model assumptions.

These studies utilize three different generations of GCMs, dating from the early 1990s, late 1990s and mid 2000s. GCM-derived climate inputs for the most recent studies (Hoerling and Eischeid, 2006, Christensen and Lettenmaier, 2006) are believed to significantly more robust than older results (Nash and Gleick, 1991, 1993) because of increased understanding and increased model resolution. In general, temperature projections are considered much more reliable than precipitation, even in the latest models. As noted by the IPCC, even with many advances over the years, global climate models still do not adequately resolve precipitation in mountainous areas. It is noteworthy, however, that the most recent GCM results for precipitation in the Colorado River basin show somewhat consistent results across models with very little change in average projected annual precipitation relative to historical conditions. Individual models do, however, show significant variability with the 11 models used in the recent Christensen and Lettenmaier paper showing a range of approximately 80% to 120% of the historical average precipitation.

Studies which used empirical/statistical relationships between temperature, precipitation and runoff (Stockton and Boggess, 1979, Revelle and Waggoner, 1983, Hoerling and Eischeid, 2006) have been criticized for failing to consider how these relationships might change in a future climate due to evapotranspiration and vegetation changes, and changes in seasonality of runoff. Such changes might substantially alter the relationships between temperature, precipitation, and runoff, which could invalidate the findings.

There have been other criticisms of studies using the historical data. Karl and Reibsame (1989) criticized Langbien's 1949 work, and derivatives thereof including Stockton and Boggess, 1979 and Revelle and Waggoner, 1983 for overstating the impact of temperature on runoff. They maintain that changes in precipitation will be far more important than temperature in determining future runoff. Much of their analysis is based on looking at decadal changes in runoff. This study was in turn criticized by Rind et al. (1990) for using average warming only 1/10 that projected for doubled CO_2. Rind et al. suggest that all studies based on the observational record are flawed because the water holding capacity of the atmosphere varies strongly with temperature – potentially up to 30% for 4C warming – and this type of widespread warming and associated increase in water vapor have no analog in the historical record.

Hydrology models can potentially overcome some of the limitations inherent in the statistical/observational approach by modeling many of the physical processes which control runoff such as snow accumulation and melt, groundwater recharge, and evapotranspiration from plants. In theory as the climate changes, these models should correctly handle new physical conditions. Unfortunately, these models require large amounts of data, much of which is imprecisely known. Furthermore, in order to resolve very complex and sometimes poorly known relationships, the models may overly simplify important physical processes. For example, the VIC model uses a two-meter subsurface layer to model all interactions with soil moisture and groundwater, despite the fact that surface water/groundwater interactions frequently involve various forms of aquifers with significant storage capacity. Finally, most hydrology models do not have land cover which can respond to changes in climate. Thus, they too might suffer from inaccuracies if the climate changes enough to affect the relationship between land cover and runoff.

Three of the studies, Nash and Gleick (1993), Christensen et al. (2004) and Christensen and Lettenmaier (2006) used an operations model to project specific water system outcomes based on their future runoff results. Nash and Gleick (1993) utilized an older version of the USBR's CRSS model and the Christensen studies utilized a model (CRRM) created at the University of Washington. While the results of these two models are intriguing, it must be noted that numerous critical policy-laden decisions about how to operate the system under low flow conditions have never been addressed and thus these implementations either ignore these issues, or implement a solution that has no standing in the Law of the River. For example, neither the bookkeeping associated with Present Perfected Rights in the Upper Basin nor shortages in Upper Basin are present in these models. Hence, modeled reservoir storage and hydropower production are directly tied to modeling decisions which may be founded on unrealistic assumptions about the management and operational strategies that would be pursued in the face of severe drought. Assumptions about reservoir starting contents also can significantly alter results. Christensen et al. (2004) noted these problems and suggest that the operational results should only be used in a comparative sense. Thus, for the purposes of this document, these operational results should be of less interest than the findings for streamflow.

All recent studies specific to the basin (Christensen et al., 2004; Christensen and Lettenmaier, 2006; Hoerling and Eischeid, 2006,) and the Milly et al. study which later produced results specifically for the CRB[7] indicate that by mid- to late-21st Century, the central expectation is for decreased runoff in the Colorado River Basin. Furthermore, when precipitation is assumed to be constant or slightly decreased, an assumption consistent with the central projections of recent studies, all past studies (Stockton and Boggess, 1979; Revelle and Waggoner, 1983; Nash and Gleick, 1991, 1993) also indicate less future runoff. However, the range of results still spans increased to decreased runoff conditions through the late 21st century (e.g., Christensen and Lettenmaier, 2006).

If future precipitation remains approximately the same or decreases slightly, it seems likely that the basin will see less runoff. This leaves open the question of the magnitude of the decline. The two most recent studies have a very large range in future declines from -11% by 2100 by Christensen and Lettenmaier (2006) to -45% projected by Hoerling and Eischeid (2006) by about 2050. Although the Hoerling and Eischeid method can be questioned for using relatively crude techniques, its calibration and verification statistics are quite good. In contrast, the Christensen and Lettenmaier study (2006) is far more sophisticated and shows some results consistent with theories such as increased winter precipitation and increased summer and fall temperatures.

The Seager et al., and IPCC findings are both based on the recent AR4 climate models and at the large scale of these studies there is also general agreement that runoff in the “American Southwest” in the future will be reduced. It should be noted that the term “American Southwest” in the case of the IPCC is not defined, and in the case of Seager et al. covers far more area than is typically associated with the reference. While it is easy to criticize these studies for using GCMs which lack the sophistication seen by many to be necessary to model the complex topography and mid-continental location of the Colorado River basin[8], their collective findings are important for several reasons. These include the large number of models agreeing on the same projections as well as supporting theories on Hadley cell expansion, storm track movement and evidence from the paleoclimate record. At the least, these efforts suggest that additional research to understand the bases for model concurrence should be undertaken. This overall paradigm of projected future dryness in an existing dry subtropical area also has analogs in other parts world including the Mediterranean. This analog does fall short, however, in explaining how a relatively wet mountainous area close to an existing dry area should respond to future warming.

Finally, it is worth emphasizing that runoff and operations impacts in the CRB are highly sensitive to projected precipitation changes. It is notable that the sign and range of projected precipitation over the CRB (e.g., Christensen and Lettenmaier 2006, Appendices A1-A2 and Figure U-23) seems somewhat insensitive to future projection period, unlike sign and range

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[7] Seager et al and the IPCC findings are excluded here because the Seager et al study did not include the Green River basin and the extent of the IPCC’s ‘Southwestern United States’ is not clear. Both of these studies did find reduced runoff likely in their respective study areas noted above.

[8] This point applies to Milly et al. as well.

of runoff change. This raises several questions. If precipitation change has no obvious trend related to warming, then what is driving the modeled period-to-period precipitation variability over the CRB? Put another way, what is the paradigm of CRB precipitation response to global and regional temperature increase? How does the fact that global atmospheric moisture should increase with global warming due to Clausius Clapyron physics apply in the CRB? The answers to both of these questions would provide a framework for analyzing GCM precipitation output. Without answers, we have limited basis for judging the band of precipitation projection uncertainty produced by GCMs. This band may be physically realistic, or it may be an artifact of having a diverse number of imprecise and adolescent GCM approaches & implementations. Section W.9.3 discusses these questions, additional current knowledge limitations and potential research paths forward.

U.7 Potential Methods for Relating Climate Change Information to Long-Term Reservoir Operations Analysis

Chapter W.5 presented impacts assessments that have been completed for the Colorado River basin. Those studies were conducted for a variety of climate change scenarios and using a number of different methodologies. This chapter categorizes method options for translating climate projections into operations response information. It then identifies analytical designs among those options that Reclamation's Lower Colorado region (LC) planning analysts might consider when using LC's planning model, CRSS (Section W.3). A number of design considerations are also discussed including climate scenario data availability, choice of runoff analysis tool, process simulation versus statistical methods for analyzing runoff response, treatment of natural water demands, and treatment of future precipitation assumptions.

U.7.1 Context

Following more recently developed methodologies discussed later in this section, a long-term operations analysis under assumed climate change would involve three core steps:

1) select a simulated climate scenario that overlaps with observed historical conditions and extends into a future planning horizon (e.g., a 1950-2100 time series), that has been bias-corrected during the historical overlap period (Section W.4.2.3), and has been spatially downscaled to a basin-relevant resolution necessary for planning;

2) relate downscaled climate conditions over the basin to natural runoff response; and

3) relate simulated natural runoff response to water supply and operations response.

Implementation of these steps follows the presumption that the tool development and validation has already been completed. More specifically, the hydrology model used in step (ii) and both the streamflow impairment scheme (if present) and operations model used in step (iii) have been calibrated, validated, and demonstrated to reproduce observed behavior of the system during some historical period. Implementation of these steps also implies that relations between runoff, precipitation, and air temperature are largely preserved as climate changes. Admittedly, climate will modulate conditions that affect these relations (e.g., potential evapotranspiration, land cover, etc), which introduces uncertainty into the analysis. Such uncertainties are discussed in Sections W.6.3 and W.6.6.

For convenience, steps (ii) and (iii) would be completed using one coupled model of basin hydrology and system operations. In practice, there is often a division between the hydrologic and operations modeling. The division exists for various reasons. Sometimes it is because hydrologic and operations models were developed relative to different historical periods. For example, runoff models are typically calibrated using reliable and recent meteorological input conditions, which typically mean calibrating models to conditions since approximately 1960. In contrast, operations models have often been developed relative to longer periods-of-record streamflow and water supply information. Sometimes geographical issues are a cause – e.g., where runoff simulations might be designed to simulate natural hydrology in a given watershed while the operations model might be developed to reflect a sub-area of the watershed where perimeter “system” inflows are affected by upstream impairments elsewhere in the watershed. An additional reason can relate to time-scale issues, where decisions in a given operations model (e.g., monthly) are made during time steps that are not consistent those necessary to simulate natural hydrologic processes, leading to challenges with model coupling. This all contributes to a likely situation of having to conduct steps (ii) and (iii) separately, with runoff simulation data being processed separately and input into the operations model.

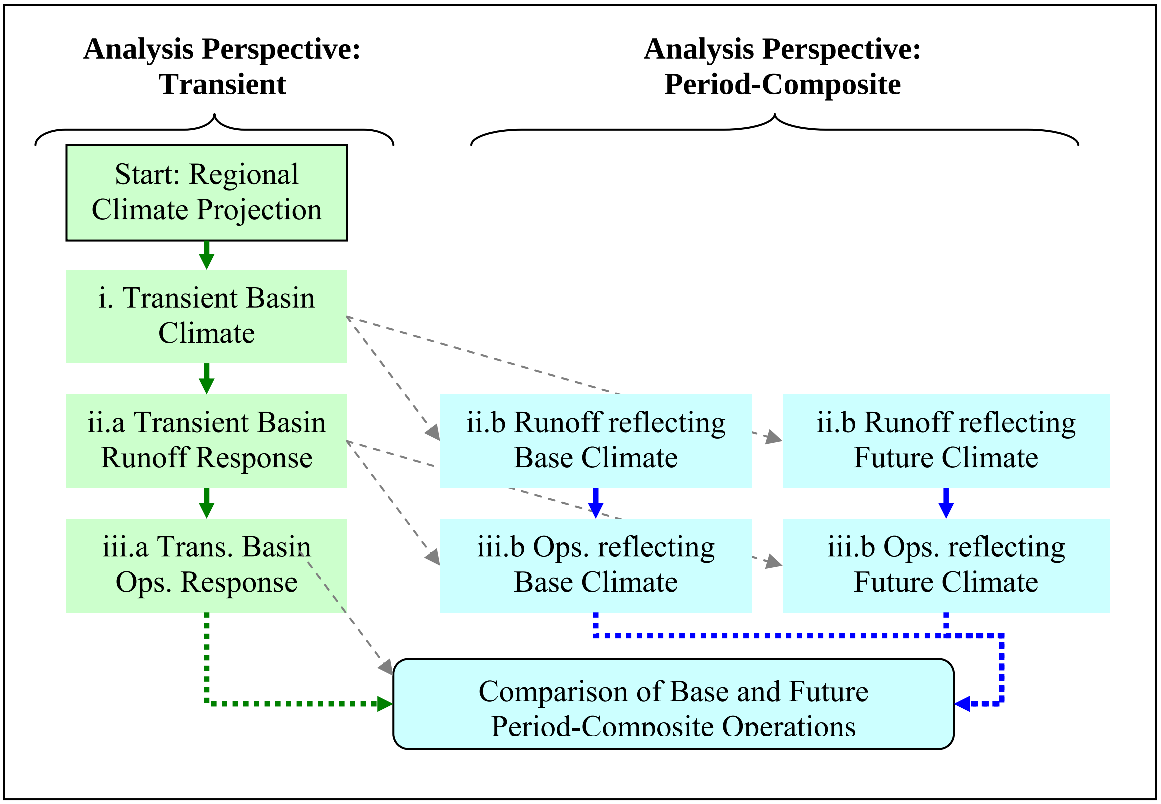
Within steps (ii) and (iii), several method options have been demonstrated in peer-review literature. For this discussion, the options are categorized under two analytical perspectives: transient or period-composite (Figure U-19). Under either perspective and considering a single-scenario analysis, the starting point is step (i) where an evolving simulated climate time-series is selected, describing historical to future evolution of climatic conditions over the basin of interest. The ending point after (iii) is comparative information describing period-composite performance of different operations variables during “recent historical” and “future” periods (e.g., variable being water deliveries to user group “A” and performance measured by long-term annual average amount). The main point is that the process starts with a transient perspective (step (i)), ends with a period-composite perspective (step (iii)), and that there are options for when to make the transition between perspectives (i.e. gray lines on Figure U-18).

U.7.2 Options for Analyzing Runoff and Operations Response

The transition can be made prior to runoff assessment, prior to operations assessment, or after operations assessment depending on the tools and methods used. Three-types of transitions are discussed in the following sections:

- Transient Runoff and Operations
- Transient Runoff and Period-composite Operations
- Period-composite Runoff and Operations

Figure U-18
Method Options for Relating Climate Change Scenario Information
to Long-Term Operations (Ops.) Response



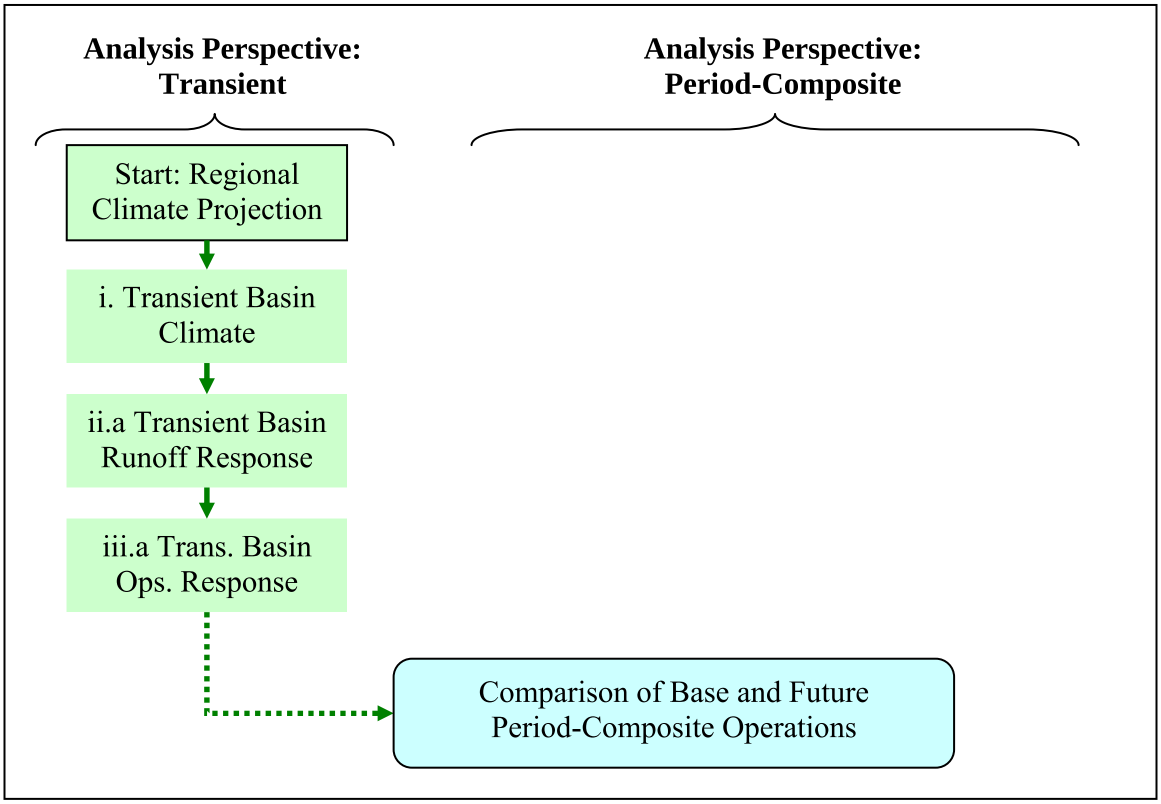
To illustrate each type, several examples from literature are highlighted in the following sections. Discussions in these sections all assume that step (ii) will be conducted using a process simulation of runoff rather than a statistical approach, although that may not be necessary, as will be discussed in Section W.6.3.

U.7.2.1 Transient Runoff and Operations

An example of this type was demonstrated by Christensen and Lettenmaier (2006), highlighted in Section W.5.1.6. Their study involved repeating steps (i)-(iii) for a 22-member ensemble of climate change scenarios. For each member, step (i) begins with a simulated climate time series having been bias-corrected relative to a 1950-1999 observed historical period and then spatially downscaled to 1/8 degree latitude-longitude resolution using methods described by Wood et al. (2004) and Maurer et al. (2007). Downscaled climate scenario time series are then converted into time series meteorological inputs for the runoff model used in the analysis, a Colorado River basin application of the Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al. 1994; Nijssen et al. 1997). Runoff results from the VIC model were then routed to key reservoir inflow and system "gain" locations in a system simulation model analogous to the Colorado River Simulation System (CRSS) (Reclamation 1985), and aggregated into monthly values at these locations, providing time series inflow inputs for scenario operations analysis. Once complete, period-composite VIC runoff and CRSS operations statistics were computed to assess runoff and operations response to climate change by measuring statistics in future relative to "recent historical" periods.

Working within the options outlined in Figure U-18, the options selected by Christensen and Lettenmaier (2006) are indicated on Figure U-19. Implementation of these options generally involves a more intensive effort to develop meteorological inputs prior to runoff analysis, but a less intensive effort thereafter as full-period runoff information for a given scenario is well-aligned with operations model input. On developing scenario meteorological inputs for VIC, the step (i) output is already at a spatial resolution and position common to the runoff model. Given that the output is monthly time-step information for only precipitation and temperature conditions, additional data processing is required to translate the data into sub-monthly timestep conditions (daily) and other meteorological inputs required by VIC (e.g., wind speeds and surface radiative variables following methods described by Maurer et al. [2002]).

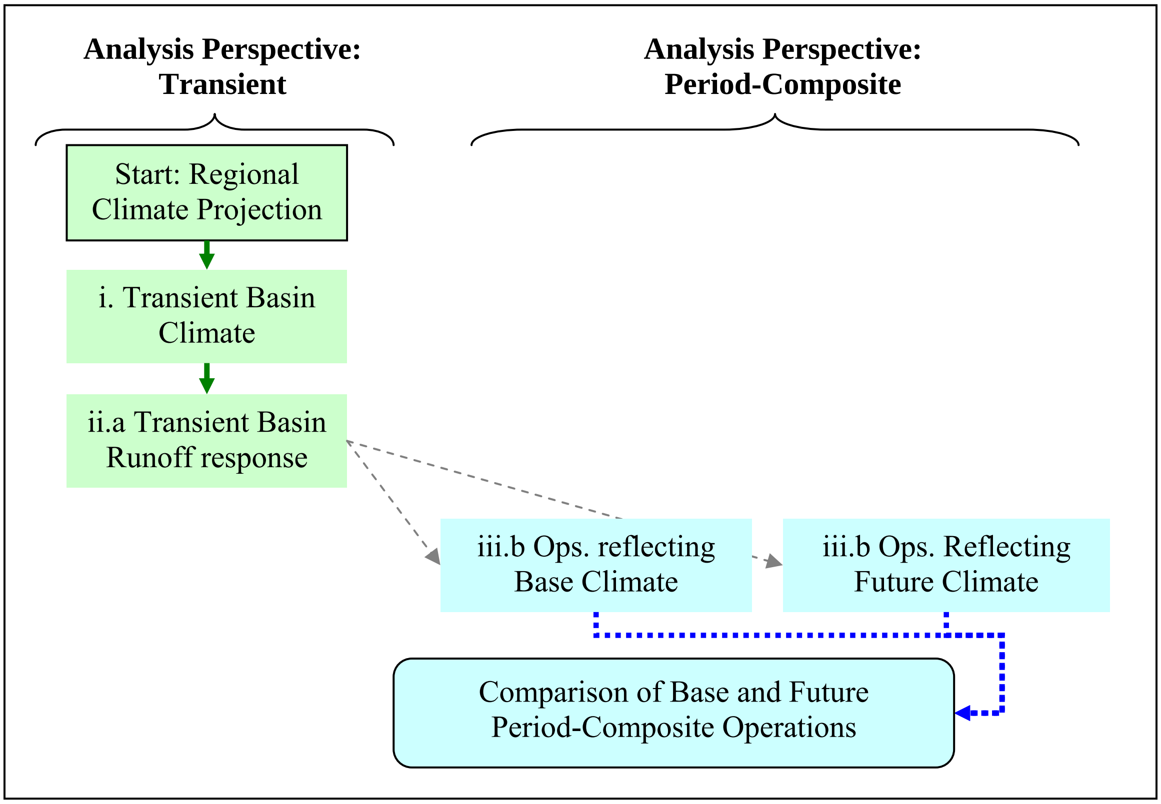
Figure U-19
Example Selection of Options following Christensen and Lettenmaier (2006)



U.7.2.2 Transient Runoff and Period-composite Operations

An example of this type was described in the California Department of Water Resources in their report "Progress on Incorporating Climate Change into Management of California's Water Resources" (CA DWR 2006). In their application, step (ii) reflected similar methods featured in Christensen and Lettenmaier (2006) and Maurer et al. (2007). Specifically, the runoff analysis was conducted using a California Central Valley application of VIC (Van Rheenan et al. 2004), and featured the same methods of preparing climate scenario meteorological inputs for the VIC application as described in Christensen and Lettenmaier (2006). The need to adopt a period-composite perspective for step (iii) was driven by the choice of operations model, which did not easily couple with the VIC application in several respects. For example, the VIC model simulated natural flow but not watershed impairments whereas the operations model simulated decisions relative to impaired river inflows at an interior sub-area of the watershed, located below other reservoir systems at higher elevation. The VIC model simulated natural flow during post-1950 conditions whereas the operations model featured a base inflow sequence coincided with observed weather during 1922-2003 and a study assumption was to continue using that historical sequence to reflect inflow variability. Consequently, rather than attempting to couple the VIC runoff model to the operations model, or adjust the base sequence of the latter, a perspective transition was implemented between steps (ii) and (iii) (Figure U-20).

Figure U-20
Example Selection of Options following CA DWR 2006



The mechanics of transition occurred using the following steps:

- Adopt “historical” and “future” periods of interest from the simulated runoff time series (CA DWR 2006 reports that simulated runoff during “1961-1990” and “2035-2065” periods were considered).

- Route VIC runoff results during these periods to key system inflow locations of the operations model.

- At each routed runoff location,

  - compute mean monthly runoff during each period.

  - compute month-specific inflow adjustment factors, defined as ratios of runoff, “future” divided by “historical” (i.e. natural runoff sensitivities).

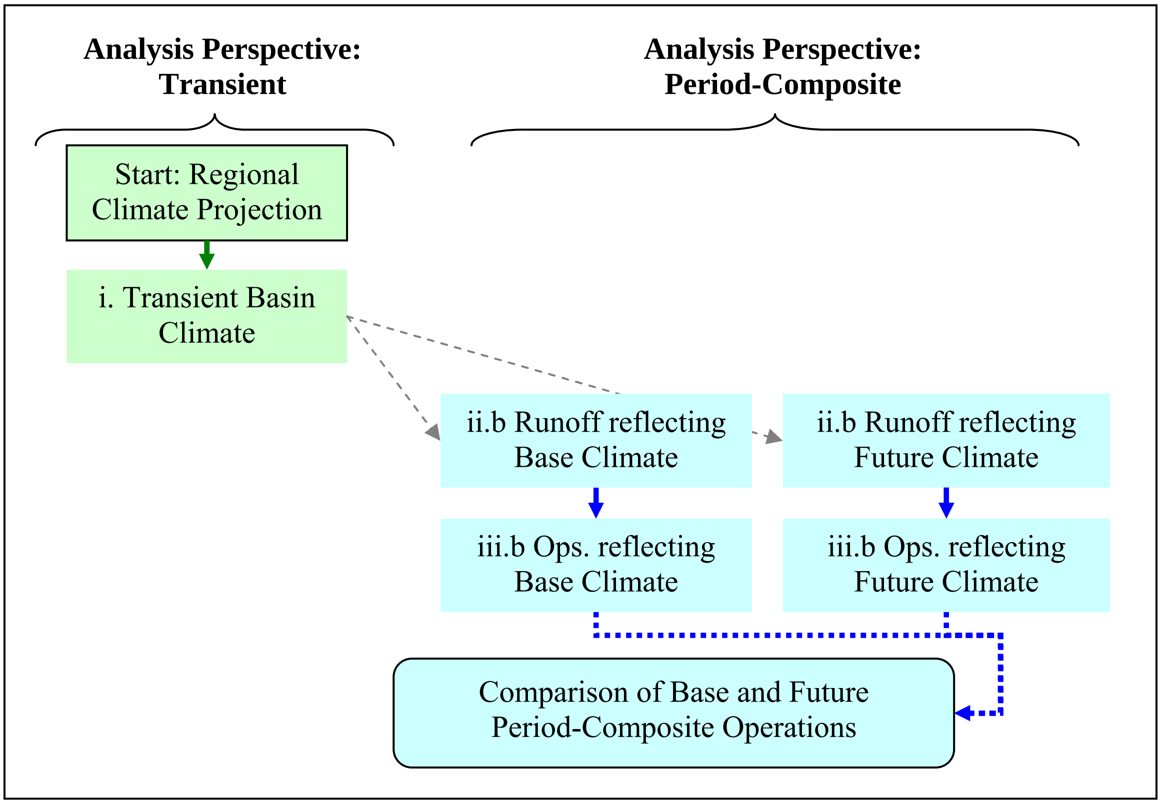
  - adjust the operations model’s “base case” inflow time series on a month-specific basis using the inflow adjustment factors. For example, at a given location, if the January ratio of runoff change is 1.2, inflate all January inflows in the operations model’s input time series by +20%.

  - As it was applied, it is understood that this approach introduced discrepancy into the analysis since natural runoff responses were used to perturb “impaired” inflows in the operations model. However, such discrepancy may be unavoidable if water management decisions upstream of the operations model’s geographic domain are not incorporated or cannot be feasibly incorporated into the operation model.

U.7.2.3 Period-composite Runoff and Operations

An example of this type is illustrated by the sequential analyses outlined in Miller et al. (2003) and Zhu et al. (2005). The operations analysis (step (iii)) by Zhu et al. (2005) follows a period-composite approach, similar to CA DWR 2006. However, the preceding runoff analysis (Miller et al 2003) also follows a period-composite perspective (Figure U-21).

Figure U-21
Example Selection of Options following Miller et al. (2003) and Zhu et al. (2005)



The starting points for the runoff analysis were (a) the simulated "monthly" climate time series over the given basin of interest, and (b) the "observed historical" basin meteorological time series at a 6-hour timestep used to calibrate the runoff model. The spatial resolution of (a) is not compatible with that of (b), requiring GIS data processing to develop monthly climate time series aggregated over the basin area. For example, in Miller et al. (2003), the information in (a) was downscaled during step (i) to a 10-km gridded resolution. These data had to be related to mean area "upper" and mean area "lower" basin areas for which the calibrated model had "observed historical" meteorological inputs. The need for this GIS exercise was set up by choice of runoff model (i.e. lumped basin applications of the Sacramento Soil Moisture Accounting (Burnash et al. 1973) and SNOW17 models (Anderson 1973) developed and provided by the National Weather Service CA-NV River Forecast Center). For these models, (b) consists of mean area "upper" (MAU) and mean area "lower" (MAL) precipitation and temperature observations from 1963-1992.

Given these starting points and a given basin, the transition from the transient to period-composite perspective in Miller et al. (2003) was accomplished as follows:

- Adopt "historical" and "future" periods in the simulated climate time series overlying the basins.

- From the simulated monthly climate time series aggregated to MAU and MAL boundaries, compute mean monthly temperature and precipitation during each period.
    - Compute month-specific shifts in temperature, future minus historical.
    - Compute month-specific ratios of precipitation change, future divided by historical.
- Create a “future period” meteorological input sequence for the given basin’s runoff model by adjusting a duplicate version of that model’s “observed historical” sequence on a month-specific basis according to mean monthly shift- or ratio-changes in temperature and precipitation, respectively. For example, given a future-minus-base January temperature change of +1.1 °C, all January time-step values in the “observed historical” sequence would be adjusted +1.1 °C. Likewise, for a given future-to-base December precipitation ratio of 1.2, all December time-step values in the “observed historical” precipitation sequence would be scaled 20% higher.

The basin’s runoff model is then simulated for both the “historical” and “future” meteorological input sequences, producing runoff output that can be compared to compute monthly inflow adjustment factors as discussed in the preceding method (Section W.6.2.2). Subsequent procedures are unchanged relative to the preceding method.

U.7.3 Analysis Design Considerations

U.7.3.1 Climate Scenario Data Availability

The public and water resource analysts (including those at LC) can access a multitude of GCM “raw output” in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, which includes projection-specific datasets that vary by GCM and by greenhouse gas scenario simulated, as discussed in Section W.4. The multi-model dataset has been made available by the Program for Coupled Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory (http://wwU-pcmdi.llnl.gov/) and WCRP's Working Group on Coupled Modeling. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Projection-specific datasets are at “climate model” resolution, which is too coarse for hydrologic and operations studies conducted by LC analysts. Before such studies can be conducted, it is necessary to bias-correct and spatially downscale the climate model output into distributed climate conditions at more local resolution (Section W.4.2.3). The availability of downscaled climate projection datasets over the Colorado River basin is currently limited. LC might acquire such data through collaboration with research groups currently studying climate impacts in the region (e.g., NOAA-RISA centers at the University of Washington (Climate Impacts Group), University of Arizona (CLIMAS) or Colorado University (Western Water Assessment)). If studies of this nature are envisioned in the future, it might be useful for Reclamation to develop the ability to perform bias-correction and spatial downscaling procedures internally.

U.7.3.2 Choosing a Runoff Model

Runoff model options range from those supporting operational hydrologic forecasting services (e.g., Sacramento-Soil Moisture Accounting and SNOW17 applications (Sac-SMA) developed for Western U.S. basins by the National Weather Service River Forecast Centers) to hydrologic simulation tools used in research (e.g., the Variable Infiltration Capacity macroscale hydrologic model applications developed for various areas in the Western U.S. (e.g., the CA Central Valley application discussed by Maurer et al, 2007; the Columbia-Snake River Basin application discussed by Nijissen et al, 1997; or the Colorado River basin application discussed in Christensen and Lettenmaier, 2006). A common trait among process simulations is that they feature an interplay of lumped and linked watershed characteristics, where watershed processes are simulated in base level units (e.g., mean area upper or lower units in NWS RFC's Sac-SMA applications or regular grid cell units in VIC applications) and runoff between these units is governed by a routing scheme.

Any model option may be suitable as long as it has been well-calibrated in the basin of interest. Model familiarity, model access, and computing requirements are likely to be factors determining which hydrologic model is preferred. Some other distinguishing factors might relate to physical representations in the model. For example, in basins where there is significant elevation variability, a higher spatial resolution model might be able to more accurately show snowpack and snowmelt response to climate change. Likewise, in basins where groundwater baseflow contributes significantly to discharge conditions during low flow months, a model with a better treatment of subsurface hydrology might be preferred.

U.7.3.3 Analyzing Runoff Response Using Statistical Resampling

It has been suggested that step (ii) could be conducted using statistical techniques rather than runoff process simulation. There are several potential motivations for a statistical approach. First, operations analysts may not have easy access or have familiarity with the runoff models and data, particularly if the latter are maintained and operated by a separate agency (e.g., Reclamation operations analysts needing access and familiarity with models and data used by NWS RFC staff). Second, the computational requirements associated with runoff simulation and data handling may be an issue for some project situations. Finally, the step of translating natural runoff simulation response into adjusted "impaired system inflows" of an operation's models may introduce significant error (although this is not a concern for CRSS application, which is forced by natural system inflows; see Section W.3).

It has been proposed that such process modeling could be circumvented if a statistical model can be identified where an historical "inflows like-year" is selected as a function of climate parameters. For example, such a model might relate seasonal runoff volumes to antecedent or coincident season(s) temperature and/or precipitation. If such a model can be rationalized, then it would be possible to force such a model using a simulated climate time series (historical or projected) to determine lookup climate conditions from a historical database of paired climate and inflows data.

An attractive aspect of this approach is that the generated inflow time series complies with both (a) simulated climate conditions, and (b) the observed historical relationship between climate conditions and system inflows. For studies involving operations models that require "impaired system inflow" inputs, this would be an improvement over the process-based approaches to step (ii) featured in Section W.6.2, where natural runoff response to climate change from the runoff process modeling was taken as proxy information for the response of the operations model's impaired inflows.

Other advantages relate to implementation and compatibility with paleoclimate information. The statistical approach would seem to be cheaper and easier to implement, as it does not involve the model setup, or likely the computational and data processing requirements associated with runoff process simulation. It would also seem to offer an easily applied framework for developing "paleo" system inflows, where the observed historical inflows-climate relation is applied with reconstructed time series of paleoclimate conditions to produce paleo-inflows. That said, until the statistical relation between observed historical inflows and climate is established, it is uncertain which paleoclimate indicators would need to be surveyed and whether sufficient indicators could be identified. Nevertheless, paleoclimate reconstructions continue to be developed, and may be applicable to this conceptual framework. For example, summer season temperature reconstructions have been reconstructed from 1600-1983 for the general area of the Upper Colorado River basin (Briffa et al. 1992). A follow up summer season temperature reconstruction for a region just north of the Upper Colorado River basin dating back to 1350 is also under development (Connie Woodhouse, 6 March 2007, *personal communication*).

A potential disadvantage of the statistical approach is that it is limited to the assumption of persisting land cover conditions associated with the observed historical inflows-climate relation. However, runoff process simulations (Sac-SMA or VIC applications) are also limited by the same assumption (discussed in Section W.6.3.3). Additional model development would be required to identify time-changing model calibrations (i.e. model parameterizations) relative to time-changing land cover during the calibration period. It is not certain whether such time-changing model calibrations could be identified.

Another potential disadvantage of the statistical approach is that its application in this context has been less developed than approaches involving runoff process simulation that have been demonstrated in peer-review literature (e.g., Miller et al. 2003, Maurer et al. 2007, Christensen and Lettenmaier 2006). The approach has been primarily developed for shorter-term (seasonal) runoff-projection applications. For example, Regonda et al. (2006) developed a statistical resampling scheme conditioned on climate predictors and applied it to prediction of runoff conditions at multiple sites. Although their prediction look-ahead was only seasonal, the use of climate variables to condition the resampling would seem to be extensible to longer-term look-ahead horizons.

U.7.3.4 Treatment of Evapotranspiration and Land Cover

In many watersheds, the loss of water from the land surface via evapotranspiration (ET) is a significant term in the surface water budget. Treatment of this term in hydrologic process-models tends to vary. For example, in the Sac-SMA applications, evapotranspiration is simulated in response to simulated soil moisture conditions and input potential evapotranspiration demands. The latter demands are area-lumped historical average values that vary with month and day during the calendar year (NWS OHD 2005). In contrast, more recently developed hydrologic models such as VIC simulate evapotranspiration based on input land cover (bare soil to various vegetation classes) and input or derived meteorological forcings (temperature, wind speed, vapor pressure, shortwave radiation, and net longwave radiation).

As temperature and radiation increases, it is reasoned that potential ET would also increase. However, coincident changes in CO_2 (which affects plant stomata response) and other surface radiative variables introduce uncertainties on this ET response. Nevertheless, if process-simulation is selected for the runoff response analysis to climate change, it would seem that the more dynamic ET simulations of recently developed hydrologic models (e.g., VIC) would be preferred for capturing dynamic ET responses to meteorological changes. If the statistical approach of Section W.6.3.2 is selected, such dynamic ET responses would be implicitly represented when statistically selecting runoff conditions based on associated climate conditions.

When discussing natural ET response to climate change, it is also relevant to discuss potential land cover changes since the landscape composition also determines watershed ET. Most available hydrologic model applications (Sac-SMA, VIC, or otherwise) treat land cover as a static condition during model development and scenario simulation. In other words, while historical period climate and runoff observations are used to calibrate hydrologic process parameters (e.g., during 1960-2000), the coincidental land cover conditions in the watershed are either period-averaged or assumed to equal a recent land cover survey. The latter assumption is likely incorrect, understanding land cover has always evolved and will likely continue to do so in the future. This raises issues for step (ii) in the analytical sequence, whether it is done with process simulation or through the statistical concept of Section W.6.3.2. That said, land cover issues may be of secondary significance in simulation of seasonal-to-annual inflows, given that models like VIC have been used to explain a considerable majority of annual flow variance (Andrew Wood, 25 May 2007, *personal communication*).

Drivers of land cover change range from societal to natural. Our capabilities to project land cover in response to societal changes have received more research attention. For example, projections for Western U.S. land cover have been developed for the year 2040, and reflect an expectation that urban areas will occupy a greater proportion of the Western U.S. landscape during the coming decades (Travis et al. 2005). Capabilities in projecting land cover response to natural changes are less developed, but there have been attempts in recent years. For example, coarse models have been developed that simulate vegetation succession in response to climate change (Bachelet et al. 2001). Other studies have been conducted on potential vegetation responses to changes in atmospheric gases composition (Iverson and Prasad 2001; other references in the U.S. National Assessment of The Potential Consequences of Climate Variability and Change – Sector: Forests (USGCRP 2000)). However, questions remain surrounding land cover response to climate change, related to characterizing land-cover dynamics, drivers behind those dynamics, and the interactions between societal change, climate change, and land-cover dynamics (USCCSP 2003).

U.7.3.5 Treatment of Groundwater and Surface Water Interactions

Rivers and groundwater are intimately connected. That said, typical methods for studying runoff response to climate change (e.g., studies cited in Sections W.5 and W.6) have not featured direct simulation of groundwater response to surface climate changes. Ideally, analysis of surface water response to climate change would be performed with knowledge of how groundwater coincidentally responds, both in terms of migration and spatial/temporal distributions of aquifer stock. In contrast, typical methods for assessing runoff response to climate change feature use of models where groundwater interactions with surface water are more implied than prescribed.

Several areas of research must be advanced further in order to permit more definitive messages about how natural runoff will respond to climate change in the context of coincidental groundwater response. It will be necessary to understand the entire recharge process and its response to climate change. This in turn will require better understanding of groundwater recharge and movement at scales relevant to regional runoff analysis, and in turn require understanding on the aggregate process of mountain block recharge (K. Redmond, 2 June 2007, *personal communication*). Further, the role of root zone and riparian vegetation in mitigating this interaction will have to be better understood, which segues into questions already posed in Section W.6.3.4 about on how basin land cover and natural evapotranspirative demand will respond to climate change.

U.7.3.6 Treatment of Future Precipitation Assumptions

Current capabilities in projecting regional precipitation response to global climate change are limited. As discussed in Section W.4, raw GCM simulations of precipitation will likely put the precipitation in the wrong places, perhaps at the wrong time, and with wrong amounts. Bias-correction and spatial downscaling can be used to remove regional GCM biases (Section W.4.2.3). However, such data-processing does not provide more reliable information or increase confidence in a particular GCM scenario for climate change.

For planning studies, the problem with GCM-simulated precipitation projections is a matter of how to regard the data rather than how to use the data. Methods on how to use the data have been developed (Sections W.4.2.3 and W.6.2). The problem is that the variation among GCM-simulated precipitation projections can be quite broad for a given study region (e.g., Figure U-9a, b showing greater than +/- 50% change intervals for annual average precipitation over the Colorado River basin). Notably, a paradigm does exist suggesting that global precipitation should increase in response to global warming because increased temperatures cause a net-global increase in evaporation and subsequently precipitation. However, at a regional scale, there’s no established paradigm suggesting *direction* or *limit* of precipitation change. Such a paradigm would have to factor in a multitude of drivers that affect the regional surface climate (e.g., for the

Colorado River basin: the influence of climate change on North Pacific storm track position, North American monsoon, tropical pacific variability related to ENSO, and other interannual/interdecadal climate phenomena that will be presented in Section W.8).

This issue is significant when conducting water management impacts analyses for storage-rich systems like the Colorado River basin. Storage-rich systems are sensitive to trends in mean-annual precipitation and runoff, more so than to changes in seasonal runoff patterns. An impact assessment conducted on such a system would produce a range of impacts significantly influenced by the range of precipitation changes considered (presumably from GCM results). Given that GCM-based precipitation changes can vary considerably (Figure U-9a, b) and may not exhibit consensus towards wetter or drier (Figure U-9a, b), some critical thought is invited as to whether the precipitation projections should be considered altogether at this stage in impacts study.

An alternative path forward might involve focus on only the more reliable aspects stemming from GCM-simulated climate projections (i.e. temperature changes), and combining this focus with either an assumption of no precipitation change or precipitation variability from some period of the observed or paleo-past (see Section W.7). Using this approach, any of the method options presented in Section W.6.2 could still be implemented, but instead with consideration limited to only GCM temperature projections and alternative methods used for defining future precipitation.

U.7.4 Potential Analysis Designs using Reclamation's CRSS

This section explores potential analytical designs that LC staff might consider, combining the use of LC's operations model, CRSS (Section W.3), with the method options discussed in Sections W.6.2 and W.6.3.

U.7.4.1 Transient Runoff and Period-composite Operations

This design would be similar to that implemented by CA DWR (2006), and illustrated in Figure U-21. It is assumed that the LC study might involve exploring how simulated operations are sensitive to a climate assumption (e.g., base versus future), or how operations alternatives vary under an assumed climate change scenario. The study might begin with selection of one or more of the scenarios and natural runoff simulation datasets recently documented in Christensen and Lettenmaier (2006). Scenario selections are subjective (e.g., choice of lower and higher rate-of-warming scenarios). CRSS inflow data preparations would follow, beginning with selection of "historical" and "future" climate periods. The results would be examined from a "period-composite" perspective, computing monthly mean runoff conditions near CRSS inflow locations during both "historical" and "future" periods. Ratios of monthly mean runoff would be computed, future relative to base period values, and be used as monthly runoff adjustment factors to scale the historical CRSS system inflows (month by month) into a future set of system inflows, reflecting observed inflow variability with means reflecting future climate.

Before developing the monthly runoff adjustment factors, the runoff datasets may need to be post-processed to report routed runoff at CRSS system inflow locations, and it may be necessary to bias-correct the routed natural runoff time series at these locations as it is possible that the modeled-historical and observed-historical natural runoff during the common historical overlap period will be different. A “distribution mapping” method could be used, similar to that discussed in section W.4.2.3 as it is used to bias-correct climate simulations (Wood et al, 2004).

U.7.4.2 Transient Runoff and Operations

This design is similar to the preceding design in that it uses the same starting points and potentially involves runoff-routing and bias-correction procedures during procedures to prepared CRSS inflow datasets. The only difference is that rather than adopt a period-composite perspective when relating Christensen and Lettenmaier (2006) runoff data to CRSS system inflows, a transient perspective is adopted instead. The time series of climate-scenario simulated runoff are routed to CRSS inflow locations (potentially bias-corrected) and used directly to force the CRSS simulation. This would permit the CRSS simulation to show how operations would evolving under evolving runoff conditions associated with the given climate scenario.

U.7.4.3 Transient Runoff and Operations with Statistical Runoff Analysis

This design would be similar to the preceding design, except that the transient runoff information under a given climate scenario would not be produced using hydrologic process simulation. Instead, statistical resampling schemes based on historical relations between observed inflows and climate variables, and driven by projected conditions for the climate variables, could be utilized to develop climate-scenario CRSS system inflows. The scenario starting points from the two preceding designs might be used here, aggregated into annual or monthly climate variable time series as required by the statistical resampling scheme. Generation of system inflows at the various CRSS inflow locations might be performed in direct relation to the climate conditions, or through an intermediate step of first relating the basin climate to Lees Ferry flow and then disaggregating spatially and temporally using procedures discussed in Prairie et al. (2007).

U.7.5 Potential Approach to First-Order Sensitivity Analysis for Near-Term Studies

For studies and decisions concerned with longer-term look-ahead horizons (e.g., greater than 20-years) and undergoing evaluation on the near-term, a *first-order* quantitative sensitivity analysis might be conducted on operations response to projected climate change. Such analysis would ideally reveal the significance of assumed climate in determining study results and informing decisions. Given Reclamation’s current limited ability to easily conduct internally produced simulations of runoff response to climate change in the CRB, such near-term studies might be framed using literature-reported projections of climate and related runoff response.

For such studies evaluated on the near-term, it is recommended that scoping of sensitivity analysis begin with a “filtered” consideration of available literature. Rather than try to frame the analysis on all climate change and runoff impacts studies that have been conducted for the CRB (e.g., representing all studies listed in Table U-3), it is recommended that the following criteria be adopted to focus the analysis:

1) require that scenario climate change projections reflect the latest IPCC assessment on future greenhouse gas emissions pathways and climate science (i.e. the Fourth Assessment Report (AR4) from the IPCC (2007))

2) require that scenario climate change projections be produced by GCMs referenced in the latest IPCC assessment (i.e. coupled atmosphere-ocean GCMs listed in Table U-7 in IPCC (2007) report from Working Group 1, "The Physical Basis for Climate Change").

3) require that an ensemble of GCM projections be considered, representing the range of available GCMs and future emission pathways reported by IPCC, and permitting consideration of uncertain climate change over the CRB and how that translates into uncertain runoff response.

4) require that GCM *projection* data be bias-corrected over the Colorado River Basin (CRB), accounting for GCM tendencies to be warmer, cooler, wetter, or drier when used to simulate 20th century (Section W.4.2.3.2, W.6.1).

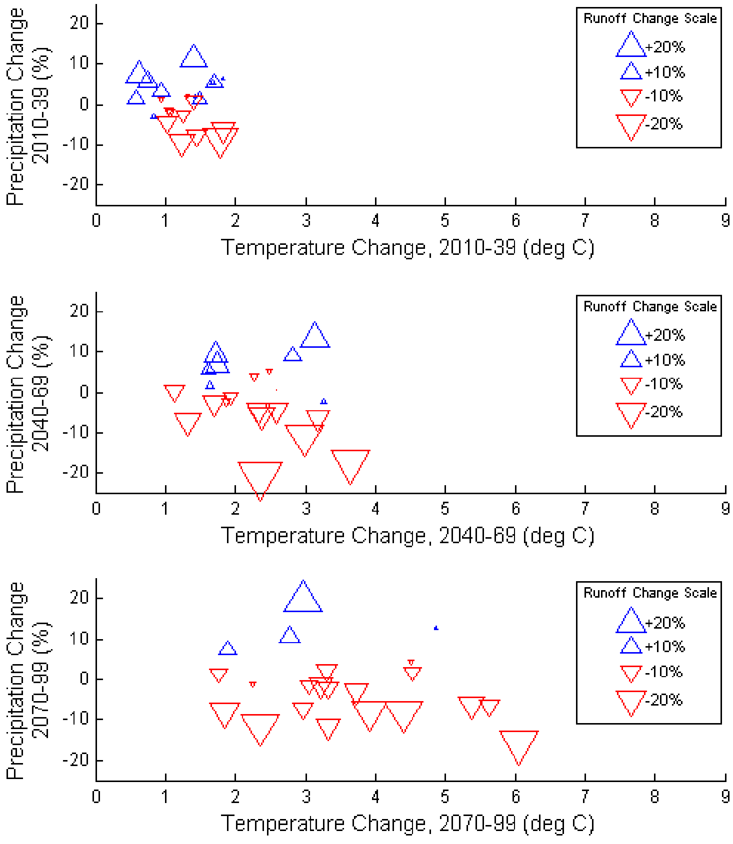
5) require that *bias-corrected GCM projection* data be spatially downscaled over the CRB, preserving larger- to smaller-scale climatic relations, and permitting more disaggregate consideration of runoff response to climate change distributed over the basin.

6) require that *bias-corrected and spatially downscaled (BCSD) GCM projection* data be translated into natural runoff response using a peer-reviewed methodologies.

Criteria 1 and 2 are meant to steer attention to the most recent understanding of climate change science and implications for the CRB. Criterion 3 recognizes that a survey of BCSD climate projections over CRB, representing multiple GCMs and emissions pathways, can reveal uncertainties of temperature and precipitation change as well as associated runoff change. Criterion 4 is based on the philosophy that simply starting from a multi-GCM projection ensemble is not sufficient, and that GCM-specific datasets should be adjusted to reflect the given GCM's tendencies to give biased climate information (i.e. revealing how the given GCM has a tendency to be too wet, dry, cool or warm when simulating past conditions). Criterion 5 is based on the philosophy that studies consider spatially distributed climate change within the CRB are better prepared to indicate spatially distributed impacts to runoff, and how these impacts aggregate to upper basin inflow to the lower basin. And finally, criterion 6 recognizes that a philosophy that literature information framing these studies should have undergone peer-review within the scientific community and that use of multiple methodologies may be appropriate to reflect model uncertainty. As for the tool choice for modeling runoff response, options exist for using statistical or process simulation. Statistical modeling may have merit in its relative ease of implementation. Physical process simulation may offer more transparent accounting of how basin-distributed climate change impacts distributed runoff, soil moisture, and evapotranspiration, as well as how evapotranspiration interacts with computed soil moisture and climate forcing conditions.

Applying these criteria to the studies mentioned in Table U-3 leads to focus on the climate scenarios and runoff changes reported in Christensen & Lettenmaier (2006) (Figure U-22). Using this information to illustrate climate and runoff change scenarios, the next recommended step is to choose a projection period relevant to the management decision being informed by the operations study. For example, the purpose of the study may be to inform evaluation of how scenario operations affect other basin resources several decades from the present (e.g., Figure U-22, top panel showing changes for early 21st Century), or how scenario operations might translate into economic value during an even longer term service life (e.g., Figure U-22, middle and bottom panels, showing changes for middle and late 21st Century).

Figure U-22
Data from Christensen and Lettenmaier (2006), (Appendices A1 and A2) Change in 30-Year Mean Annual Runoff (%) from Historical (1950-1999), Given 22 Projections of Mean-Annual Climate Change Over the CRB, Sampled for Three Future Periods: 2010-39, 2040-69, and 2070-99



The 22 projections were simulated by 11 GCMs, each simulating either SRES A2 and B1 greenhouse gas emissions.

After filtering the literature information by the projection period of interest, the next step might involve characterizing distributional aspects of period-mean climate and runoff across projections considered in the literature (Figures U-23 through U-25). This step focuses attention on change in mean annual runoff as it relates to underlying scenarios of climate change. Change in *runoff seasonality* or *variability* is not the focus in this example, which may be appropriate for CRB studies that depend on assumptions of aggregate upper CRB runoff into Lake Powell, which is more sensitive to trend in mean annual runoff than trend in runoff seasonality.

Figure U-23
Histogram and Box-and-Whisker Distributions of 2010-39 Precipitation Change relative to Historical (1950-1999) Corresponding to Scenarios Represented on Figure U-23

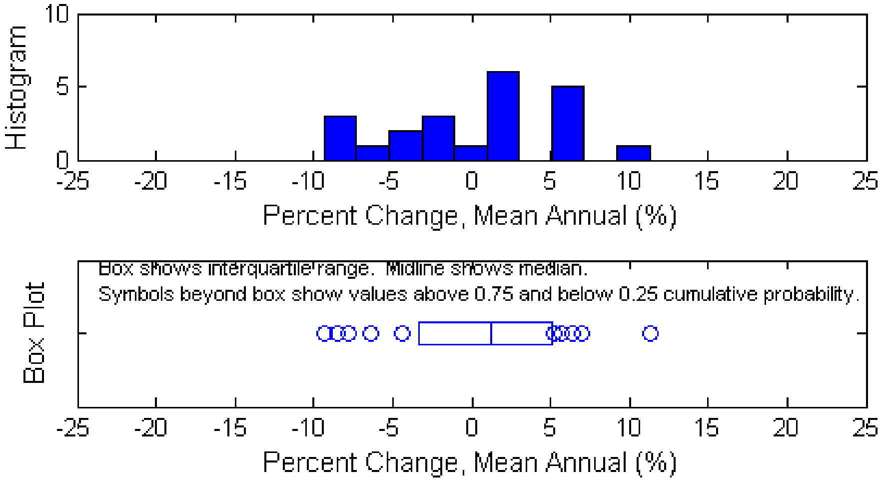


Figure U-24
Histogram and Box-and-Whisker Distributions of 2010-39 Temperature Change Relative to Historical (1950-1999) Corresponding to Scenarios Represented on Figure U-23

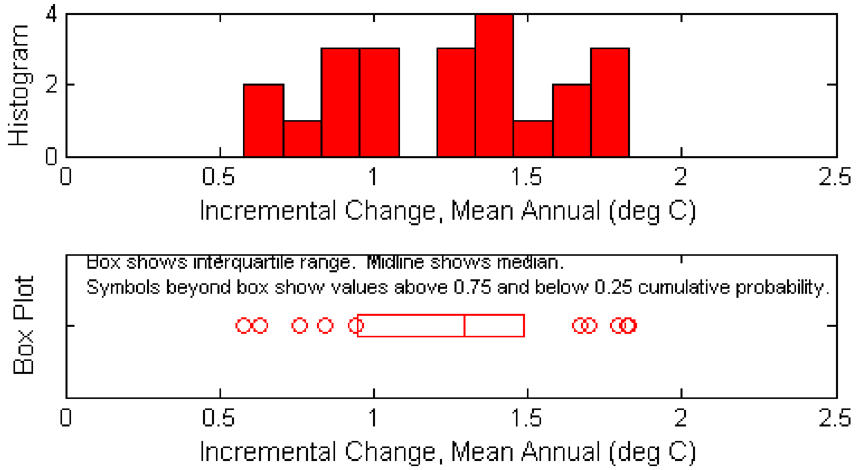
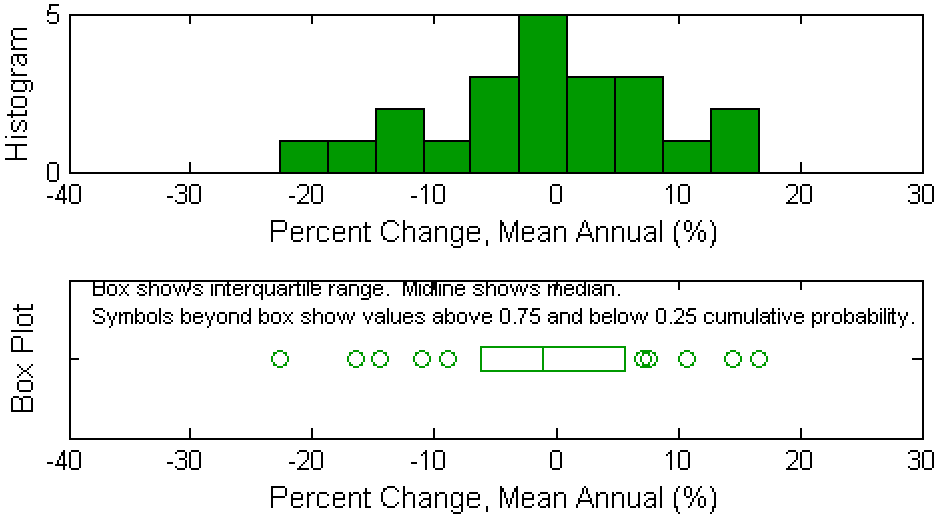
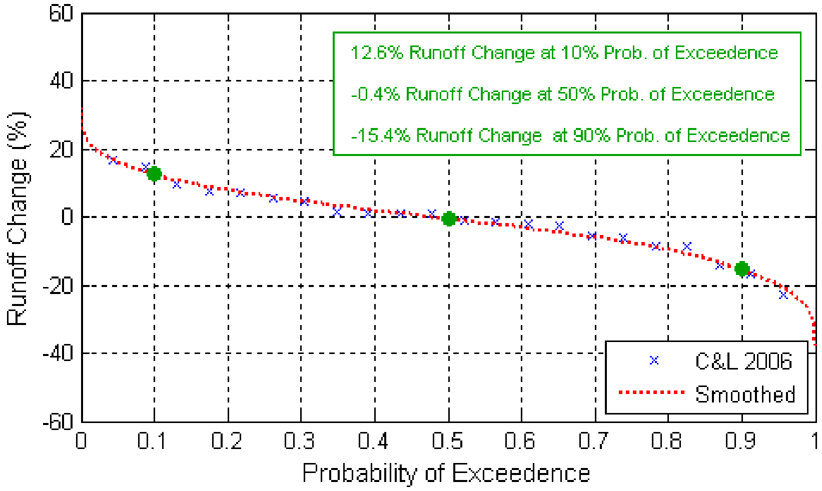


Figure U-25
Histogram and Box-and-Whisker Distributions of 2010-39 Runoff Change relative to Historical (1950-1999) corresponding to Scenarios represented on Figure U-23



After identifying these period-mean changes, the final step in setting up the sensitivity analysis is to construct a (optionally smoothed) empirical distribution of period mean-annual runoff change (Figure U-26), and adopting "risk-perspective" threshold for sampling runoff change from the smoothed empirical distribution. On this latter step, a risk-neutral decision-maker might focus on median projected change in the distribution. A risk-averse decision-maker might focus on temperature change exceeded by only 10 percent of the projections, or precipitation change exceeded by 90 percent of the projections. Upon identifying threshold annual runoff changes, sensitivity analyses could be conducted where CRSS monthly inflows (Section W.3.1) are scaled by threshold scenario changes in period mean-annual runoff.

Figure U-26
Smoothed Empirical Distribution of 2010-39 Runoff Change (%) Relative to Historical (1950-1999), Fit to Scenario Runoff Changes Shown on Figure U-26 (labeled here as C&L 2006)



Three example thresholds of runoff change are shown (green circles), as sampled from the Smoothed Empirical Distribution, where smoothing was accomplished by fitting a nonparametric density function to the 22 cases fitting cases (C&L 2006). (Note: "Probability of Exceedence" in this case represents *relative* probability based on surveyed projections and runoff analyses, not *absolute* probability.)

U.7.6 Uncertainties

The process of relating projected climate change to operations response involves a number of uncertainties introduced by the methods outlined above. These uncertainties interact with those discussed in Chapter 4.0 concerning development of downscaled climate projections and simulated climate time series. Some key uncertainties associated with analyzing runoff and operations response include:

- Assumptions on how to convert simulated climate time series into a meteorological input sequence for runoff analysis. For process-simulation, this can involve temporal disaggregation and variable extrapolation depending on the hydrologic model used.

- Assumption on where to make the perspective transition from transient to period-composite (e.g., before step [ii], before step [iii], or after step [iii]).

- Assumptions on how to structure the hydrologic model used in the analysis, with suitability of structure indicated by model skill and calibration metrics produced during model development (e.g., the ability to reproduce observed runoff given observed weather conditions).

- Assumptions for relating climate change responses in natural runoff to adjusted "impaired system inflows" in operations analysis.

- Assumptions on how to structure the operations model used in the analysis, indicated by model verification efforts (e.g., the ability to approximate real-life decisions occurring on variable daily to weekly time-scales in the context of a decision model with a uniform daily or monthly time-scale).

- Assumptions on how to represent system operations within the operations model under a changing climate, understanding that climate changes may trigger different operational strategies and discretionary operational "rules" not present in the "present climate" rendition of the operations model.

- Assumptions that historical land covers underlying both runoff and operations model development will represent future period land cover, and that historical relations between the meteorological forcings and runoff will persist.

U.8 Paleoclimatic Information for the Colorado River Basin

With the growing recognition of the inadequacy of the gaged record as a baseline for planning, the use of paleoclimatic data has received increased interest in the water resources profession. Previous sections of this report (W.3.4.2. and W.3.4.4.) described the use of paleoclimatic data in Reclamation hydrologic analyses, capitalizing on the extended perspective on past hydrology provided by these data. In addition to "looking back" up to 500 years or more, there is potential for using these data to look forward and evaluate potential future hydrologic scenarios. This section summarizes the state of science for paleoclimatic information in the Colorado River basin and how this might be used with future climate projections.

U.8.1 Paleoclimate Indicators of Hydrology in the Colorado River basin

Paleoclimatic data from environmental records can be used to extend instrumental records back in time. Tree rings are the best source of high resolution, precisely-dated proxy records of hydroclimatology over the past centuries, and they have proven useful for reconstructing a range of hydroclimatic variables, including temperature, precipitation, and streamflow (Meko and Woodhouse, 2007). In the Upper Colorado River basin, tree-ring data have been used to reconstruct streamflow over the past five centuries and longer using dendrochronological techniques.

Research exploring the relationships between annual streamflow and tree growth began in the 1940s with Edmond Schulman whose early work investigated the feasibility of tree rings as a proxy for streamflow. He was motivated, in part, by the need for an extended record of Colorado River flow to assess the reliability of long term power generation, addressed in a 1942 report he authored for the Los Angeles Bureau of Power and Light entitled "A tree-ring history of runoff of the Colorado River, 1366-1941" (Schulman 1945, Stockton and Jacoby (1976). Later work expanded upon this (Schulman 1945, 1951, 1956).

The first reconstructions for the Colorado River based on a statistical calibration of tree-ring data with the natural flow records were undertaken by Stockton in 1975, and updated with additional tree-ring data by Stockton and Jacoby in 1976. Stockton and Jacoby (1976) generated three versions of a Lees Ferry reconstruction, based on two different gage records.

They considered an average of the two reconstructions based on the common time period 1914 to 1961 to be the most reliable estimate of past flow. This reconstruction, which extended from 1521-1961, was the basis for a set of multidisciplinary studies that assessed the impacts of a severe sustained drought on hydrologic, social, and economic impacts sectors (Young 1995 and others). Two more recent studies used similar sets of tree-ring data (all with the common tree-ring end date in the early 1960s) but different statistical approaches to reconstruct Lees Ferry flow. These resulted in reconstructions that shared the main features of Stockton and Jacoby's reconstruction but varied with regard to the magnitude of the high and low flows (Michaelsen et al. 1990, Hidalgo et al. 2000). (See Table U-6 for a summary)

Woodhouse et al. (2006) used an updated and expanded set of tree-ring data and a variety of data treatment and reconstruction approaches to reconstruct Lees Ferry flows extending from 1490-1997. Most recently, Meko et al. (2007) expanded the work of Woodhouse et al. (2006) to extend the reconstruction of Lees Ferry flow back to AD 762 using remnant material (stumps, logs, and standing dead trees) along with living tree chronologies using a nested reconstruction approach (See Figure U-27). This reconstruction, which extends seven centuries prior to any of the previous reconstructions, allows the first assessment of Colorado River flows during a period of time known as the Medieval Climate Anomaly (e.g., Cook et al, 2004). During this period, approximately AD 900-1300, the reconstruction documents a period of sustained low flow in the 1100s that includes a stretch of 62 years with a marked absence of any high flow years.

This set of reconstructions illustrates the robustness of the estimated flows with regard to the temporal pattern of flow over the past five centuries. One difference between the reconstructions is the long-term averages, which range from 13.0-14.7 maf, all of which are significantly less than the gage records average, 1906-1995, 15.2 maf.

U.8.1.1 Scientific Basis and Methodology

Tree-ring based reconstructions of Colorado River flow build upon the strong association between the annual ring widths of low elevation conifer species, (primarily *pinus ponderosa, pinus edulis,* and *pseudotsuga menzeseii*) and water year streamflow (Schulman 1956, Hidalgo et al. 2001). These conifers, particularly those growing on arid slopes with rocky soils, are sensitive to the same climate conditions that contribute to water year flows, primarily winter snowpack, but also precipitation and evapotranspiration over the course of the water year streamflow (for more detailed discussions on tree growth and streamflow, see Meko et al. 1995). In the field, careful site selection and sample replication (about 20 trees per site are cored, taking two cores per tree) further enhance the common signal, related to hydroclimatic variability, in the trees.

Table U-6
Summary of Lees Ferry Reconstructions

Reconstruction	Calibration years	Source of gauge data	Chronology type[c]	Regression approach[d]	Variance explained	Reconstruction years	Long-term mean[e] MAF
Stockton and Jacoby (1976)	a.1899-1961	Hely, 1969	Standard	PCA with lagged predictors	0.75	1512-1961	14.15
	b.1914-1961	Hely, 1969	Standard		0.78	1512-1961	13.9
	c.1914-1961	UCRSFIG, 1971	Standard		0.87	1511-1961	13.0
	Average of b and c					1520-1961	13.4
Michealsen et al. (1990)	1906-1962	Simulated flows[a]	Residual	Best subsets	0.83	1568-1962	13.8
Hidalgo et al. (2000)	1914-1962	USBR, see Hidalgo et al. 2000	Standard	Alt. PCA with lagged predictors	0.82	1493-1962	13.0
Woodhouse et al. (2006)							
Lees-A	1906-1995	USBR[b]	Residual	Stepwise	0.81	1490-1997	14.7
Lees-B	1906-1995		Standard	Stepwise	0.84	1490-1997	14.5
Lees-C	1906-1995		Residual	PCA	0.72	1490-1997	14.6
Lees-D	1906-1995		Standard	PCA	0.77	1490-1997	14.1
Meko et al. (2007)	1906-2003	USBR[b]	Residual	2-step regression with PCA	0.60	762-2003	14.7[f]
	1906-2002				0.74	1182-2002	
	1906-2002				0.77	1365-2002	
	1906-2004				0.57	1473-2005	

NOTES:

[a] *Simulated flows developed from the U.S. Bureau of Reclamation's Colorado River Simulation System.*

[b] *J. Prairie, USBR, personal communication, 2004 (Woodhouse et al,), 2006 (Meko et al).*

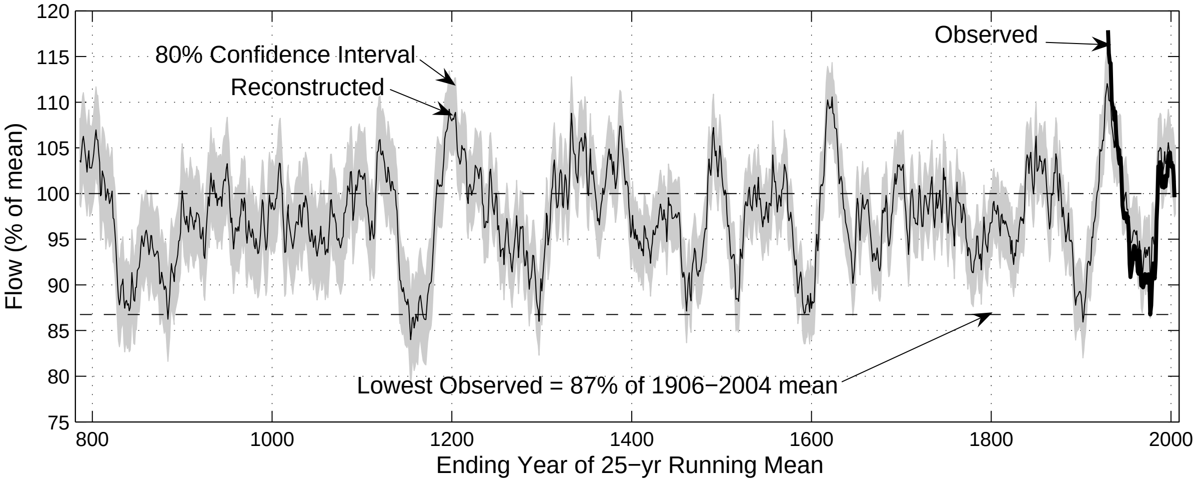
[c] *Standard chronologies contain low order autocorrelation related to biological persistence; residual chronologies have been prewhitened and contain no low order autocorrelation.*

[d] *Regression approach: PCA is principle components regression. Best subsets is multiple linear regression, using Mallow's Cp to select best subset. Alternative PCA used an algorithm find the best subset of predictors on which to perform PCA for regression. Stepwise is forward stepwise regression.*

[e] *Long-term mean based on 1568-1961 except for Michaelsen et al., 1990, based on 1568-1962*

[f] *Long-term mean is from full nested reconstruction*

Figure U-27
Reconstruction of Lees Ferry streamflow from Meko et al., 2007



A tree-ring chronology, which is derived from the average of the dated, measured, and standardized (to remove age/size related trends) tree-ring samples from a single site (Cook and Kairiukstis, 1990; Stokes and Smiley, 1968), is the basic unit used for streamflow reconstructions. Chronologies often contain significant low order autocorrelation, believed to be at least partially biological in origin, which may be removed through autoregressive modeling (chronologies with this persistence removed are residual chronologies, while those with persistence retained are standard chronologies). Tree-ring chronologies, which have been screened for a stable and significant relationship with streamflow, are calibrated with a natural flow record, typically using some type of multiple linear regression (see Loaciga et al., 1993 for a review of these approaches). Models generated through the calibration process are validated with independent data withheld from the calibration or through cross-validation, which tests the skill of the set of chronologies used rather than the specific model. Models are also evaluated to ensure results meet the assumptions of multiple linear regression.

A number of preliminary models may be generated using different data treatments (e.g., removal of persistence or not), different sets of predictor chronologies, and/or different regression approaches. The final model is selected on the basis of the amount of variance explained and the validation results. The full reconstruction is produced by applying the full-length chronologies to the selected regression equation.

U.8.1.2 Uncertainties

Uncertainty is inherent in the reconstruction because the tree-ring data are not perfect predictors of streamflow. The model uncertainty is the unexplained variance, and error bars for the reconstruction can be estimated from the average difference between the gage and estimated values. Model uncertainty is only one source of uncertainty. Other sources can come from changes in tree-ring sample size with time, the set of chronologies used as potential predictors, data treatment (including standardization which affects the preservation of low frequency information), modeling choices, the calibration period used, and the quality of the gage record. Uncertainty related to changes in tree-ring sample size over time can be reduced by truncating series when the strength of the common signal in the samples reaches a threshold, commonly 85%. The sensitivity of the reconstruction to data treatment, modeling choices, and calibration period can be assessed by comparing reconstructions generated in different ways (for an example of this, see Woodhouse et al. 2006, who evaluated reconstructions generated with different pools of chronologies, standard and residual chronologies, and stepwise and principle components regression). In addition, reconstructed flows that are higher or lower than the range of values in the gauge record may be based on tree-ring values beyond the "predictor space" on which the model is based and are thus potentially less reliable than other reconstructed values (Graumlich and Brubaker, 1986; Meko and Graybill, 1995; Meko et al., 1995).

U.8.1.3 Data Availability

Tree-ring data used in the reconstructions of the Colorado River at Lees Ferry are available through the National Climatic Data Center, Paleoclimatology Branch, International Tree-Ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html) in both uncompiled ring width measurement files and the tree-ring chronologies. The reconstructions of Lees Ferry from Stockton and Jacoby (1976),Woodhouse et al. (2006), and Meko et al. (2007) are also archived in the NCDC Paleoclimatology Branch and are available online (http://www.ncdc.noaa.gov/paleo/recons.html#hydro).

U.8.2 Applications of Streamflow Reconstructions to Water Resource Management

Tree-ring based reconstructions of streamflow are being applied in a variety of ways to water resource management. These approaches correspond well to Ray's (2004) categorization of four types of use of climatic information: *consulted*, when information is received or looked up; *considere*d, when information is potentially influential to decisions; *incorporated*, when information is actually used in an operational model for decision-making; and *communication of risk*, when the information and its implications are conveyed to others to prompt or justify action. For example, the Denver Water Board is incorporating reconstructed streamflow data into their water system model to test the ability of the system to meet demands during a broad range of conditions. They have found that the most severe drought in the reconstruction would require level 4 conservation measures. At the other end of the spectrum, the Rio Grande Water Conservation District is still in the process of considering the information provided by the reconstruction, and this information may yet become a part of their decision-making process in assessing sustainable pumping. Other water providers are using the information to advise planning and prompt boards to recognize the potential risks of drought, based on the record of the past (Woodhouse and Lukas 2006).

Paleohydrologic reconstructions from tree rings provide a record of long-term natural variability, with a broader range of values, especially with regard to drought characteristics, than provided by the gage record alone. In addition, these reconstructions provide a richer variety of sequences of annual flows, that include a greater persistence of below or near average years than in the gage records, that particularly test water supply systems. Although the climate of the past is unlikely to be replicated in the future, there is no reason to believe that the range of variability and sequences that have occurred in the past could not recur in the future. The latest IPCC reports a widespread increase in extreme precipitation events and increases in evaporation across many areas of the U.S., along with drier conditions in the Southwest in the future (Christensen et al. 2007). Taken together, these conditions may lead to a broader range of hydroclimatic variability, in which case, the extended records of flow provide a useful analogue for future variability. Consequently, this information can play an important role in helping to anticipate the nature of future droughts.

Reclamation, recognizing that the gage record contains only a subset of the flow conditions that have occurred in the past, is utilizing the reconstructions of Colorado River at Lees Ferry in modeling studies of the Colorado River system. In one case, the broader variety of sequences of flow years in the reconstructed flow record, including longer dry spells, is being incorporated into model input (see section W.3.4.2). In another approach, the full range of reconstructed values as well as the sequences of flow are being used in the modeling (see section W.3.4.4.).

The low frequency (decadal to multidecadal) characteristics in the tree-ring based reconstructions, which represent long-term natural variability, may be exploited to project future flows. For example, Kwon et al. (2007) used spectral analysis to define dominant spectral peaks in reconstructions for southern Florida, and then extracted these using wavelet analysis. The spectral information was then combined with simulated flow projections based on the autocorrelation structure in the reconstructions to generate scenarios of future flows. This approach assumes that the underlying low frequency variability in the past flows will continue into the future, but as of yet, there is no reason to believe this is will not persist.

With regard to climate change projections, experiments that utilized tree-ring based reconstructions to run water supply models which are then altered to simulate warming are being performed (Smith et al. 2007). Incremental warming is added to test the ability of a water supply system to meet demands (in this case, the City of Boulder system). Increases are then compared to those projected for the region from range of general circulation models (GCMs). This approach utilizes the broader range of hydroclimatic variability that has occurred in the past and is likely to occur in the future, along with the certain increase in temperature due to the human-induced global warming. To date, models are not yet able to replicate regional precipitation very well, and model projections of the regional precipitation response to global warming are inconsistent. Consequently, combining the variability in the paleohydrologic records with the more certain future warming seems to be a productive approach for assessing possible future scenarios.

Seager et al. (2007) argue that model results indicate a consensus that a warmer climate will cause a general aridification of southwestern North America. Seager et al. hold that periodic droughts will still occur, precipitated by oscillations in climate conditions, but these will be perturbing a drier base state (See discussion in Section W.4.4.2). Seager et al.'s work provides support for using paleohydrologic reconstructions of streamflow as a proxy for the pattern of future inflows. Their notion that a drier base state will continue to be modulated by droughts caused by climate oscillations supports an assumption that the variability in streamflow captured by the paleohydrologic record can be used (with caution) as one proxy for the variability of future flows. Thus, an approach like the non-parametric paleo-conditioned method (NPC, described in Section W.3.4.2) could be adapted to synthesize streamflow data consistent with Seager et al.'s conclusions by scaling the flows to reflect the drier base state he projects will occur. Seager et al. estimate that precipitation minus evaporation (P-E) will decrease approximately 10% by the 2060-2080 timeframe. This is in the middle of the range of changes to streamflow projected by others, as summarized in Section W.5, and lends support to changes in streamflow of that magnitude.

U.9 Interannual/Interdecadal Climate Variability

There is an increasing awareness that in addition to gradual changes (long-term trends) in climate conditions, there is also a large degree of interannual and interdecadal variability in climate which may dominate the climate experienced in a basin in the short term (10-20 years in the future). This section describes the major modes of interannual/interdecadal variability, summarizes studies that have linked these to hydrologic variability in the Colorado River basin, and discuss the predictability of these phenomena.

U.9.1 Description of Major Modes of Climate Variability

The identification of major modes of interannual/interdecadal climate variability has been an ongoing area of research. Currently the NOAA Earth System Research Laboratory at (http://www.cdc.noaa.gov/ClimateIndices/List/) archives a wide range of climate indices representing oceanic and atmospheric variability. The major modes of interannual/interdecadal climate variability that have been investigated for possible linkages in the Colorado River Basin include the El Niño-Southern Oscillation (ENSO); the Pacific Decadal Oscillation (PDO); the Atlantic Multidecadal Oscillation (AMO); the Pacific North America, and the North Atlantic Oscillation (NAO). These phenomena have frequencies that vary from 2-80 years. Other climate indices may be significantly correlated with Colorado River Basin hydrology; however, there have not been studies to document these linkages.

ENSO is a contraction of names of two phenomena that were recognized to be different expressions of the same process: "El Niño" refers to anomalous strong warming of the surface waters of the eastern equatorial Pacific Ocean, while "Southern Oscillation" refers to concurrent changes in surface barometric pressure in the tropical Pacific. The ENSO phenomenon is now understood to span the equatorial Pacific and to have opposite phases with a 2-7 year periodicity, and with impacts that occur in many parts of the world. The warm phase of ENSO is called El Niño, while the cold phase is called La Niña (Philander 1990). Common indices used to describe ENSO conditions include the Southern Oscillation Index (SOI), equatorial Pacific sea surface temperatures (e.g., NINO12, NINO3), the Multivariate ENSO index (MEI), and the Oceanic Niño Index (ONI).

The **PDO** is a pattern of ocean variability in the North Pacific that is similar to ENSO in some respects, but has a much longer cycle (20 - 50 year) (Mantua et al., 1997, Mantua and Hare, 2002). Specifically, it is defined as the standardized difference between sea surface temperatures (SSTs) in the north-central Pacific and Gulf of Alaska.

The **AMO** is defined as the leading mode of low frequency, north Atlantic Ocean (0 to 70°N) sea surface temperature (SST) variability with a periodicity of 65 to 80 years (Kerr, 2000; Gray et al., 2003). Any linear trend in the data has been removed, so the time series represents a natural variability absent of long terms trend from global warming. Research has the AMO correlated with the number of tropical storms in the Atlantic and rainfall in Florida.

The **PNA** is one of the largest-scale ocean-atmosphere patterns that varies on seasonal, interannual, and interdecadal time scales. The PNA is a measure of atmospheric pressure anomalies at four locations in the northern hemisphere (Horel and Wallace 1981). The pressure near the Aleutian Islands and the southeastern U.S. have the same sign pressure anomaly, and the pressure near Hawaii and central Canada have the opposite sign pressure anomaly. The PNA index is a standardized measure of these pressure differences and is most pronounced in the winter and disappears in the summer months of June and July.

The **NAO** is an oscillation of pressure differences between the subtropical high pressure system located in the tropical Atlantic near the Azores and the subpolar low pressure system located near Iceland (Hurrell, 1995). The difference in surface pressure generally influences the surface winds and the steering of storms from west to east. The NAO has quasi-biennial and quasi-decadal periodicity (Hurrell and Van Loon, 1997).

U.9.2 Interannual/Interdecadal Signals in the Colorado River basin

The influence of interannual (e.g., ENSO) and interdecadal (e.g., PDO, AMO, NAO) variability on the hydrology of the Colorado River basin has been studied since the late 1980s. The linkages between these modes of variability and Colorado River Basin climate is a statistical relationships and the actual mechanisms still need to be understood.

A summary of the potential impacts are noted in Table U-7. First, the relationships between ENSO and western U.S. hydrology were studied by several researchers (e.g., Cayan and Peterson, 1989; Redmond and Koch, 1991; Cayan and Webb, 1992; Kayha and Dracup, 1993; Piechota and Dracup, 1996). In the Colorado River basin, El Niño events bring generally wetter conditions to the Lower Basin and La Niña events, drier conditions. The linkage of ENSO with conditions in the Upper Basin is not as clear. The wet/dry relationship does not hold true for all ENSO events and the strength of the event can influence the general relationship. For instance, the 1982/83 El Niño event was one of the strongest on record and much of the basin (upper and lower) experienced wet conditions. However, the recent 2002 El Niño event corresponded with dry conditions in much of the basin for 2002 and 2003. This was part of an ongoing drought that started in 2000.

Table U-7
Summary of Hydrologic Conditions During ENSO, PDO, AMO and NAO Phases
and Coupled Impacts for the Colorado River Basin

	ENSO Phase		PDO Phase		AMO Phase		NAO Phase	
	+	-	+	-	+	-	+	-
All Years	Dry	Wet	Wet	Dry	Dry	Wet		
El Niño (-)	--	--	Wet					
La Niña (+)	--	--		Dry	Dry	Wet	Wet	Dry
AMO +				Dry	--	--		
AMO -		Wet	Wet		--	--		

Blank boxes represent no significant impact to hydrologic conditions. Dashed boxes represent coupling that is not possible (e.g., AMO+ and AMO+)

More recently, researchers have investigated other oceanic/atmospheric phenomena such as the AMO, PDO, and NAO. The strongest relationships have been found with the AMO. When the AMO is in a positive phase, dry conditions were noted in the Colorado River basin, while the negative phase was associated with wet conditions (Enfield et al., 2001; McCabe et al., 2004; Hidalgo, 2004; Tootle et al., 2005; Hunter et al., 2006; McCabe et al., 2007). A weaker relationship is present between streamflow and the PDO. During the PDO positive phase, wet conditions occurred in the basin, and the negative phase had dry conditions (McCabe and Dettinger, 2002; Hidalgo and Dracup, 2003; McCabe et al., 2004; Hidalgo, 2004; Tootle et al., 2005; Hunter et al., 2006; and McCabe et al., 2007). A limitation in much of this research on AMO and PDO is that the analysis contains only 1-3 cycles of the multidecadal oscillations, so the confidence in the results is not as strong as ENSO studies. The use of paleoclimatic data may enhance the understanding of these multidecadal phenomena.

The coupled relationships between ENSO and the PDO, AMO, and NAO have also been evaluated. These studies focused on coupling the interannual variability present in ENSO with longer term (decadal) variability present in the PDO, AMO, and NAO. The coupling of ENSO and PDO has been shown to result in enhanced (diminished) wet conditions during El Niño events when PDO is positive (negative). Similarly, the dry conditions during La Niña are diminished (enhanced) when the PDO is positive (negative) (Gershunov and Barnett, 1998; Hidalgo and Dracup, 2003; Tootle et al., 2005; Hunter et al., 2006). However, Rajagopalan et al. (2000) examined the coupled effects of ENSO and PDO on summer season Palmer Drought Severity Index (PDSI) values for the U.S. and determined that PDO does not enhance (or dampen) ENSO’s effect.

The coupling of ENSO and AMO has been studied by Tootle et al., (2005), and Hunter et al., (2006). During La Niña years with a positive AMO phase, dry conditions occurred in the basin. This could likely be enhancement of drought conditions since La Niña years and AMO positive years are both associated with dry conditions. During the La Niña years with a negative AMO phase, wet conditions were noted in the Upper Colorado River basin (Hunter et al., 2006). The reversing of La Niña impacts (dry) was also noted by Hunter et al., (2006) in SWE values during La Niña years that corresponded with NAO positive years. In addition, La Niña years associated with NAO negative years had dry conditions.

Lastly, AMO and PDO have been noted as possibly coupled and leading to enhanced or diminished impacts to hydrology. For instance, Hidalgo (2004), McCabe et al., (2004), and McCabe et al., (2007) found that dry conditions occurred during AMO + and PDO – phases. In addition, Hidalgo (2004) found that wet conditions occurred during AMO – and PDO + phases. This represents enhancement of wet or dry conditions when the PDO and AMO phases are opposite in sign.

A clear understanding of the dynamics behind the couplings between these circulation indices and between the indices and Colorado River basin climate is still lacking. More research is needed to better understand how these indices and the circulation features they describe impact the basin climate and hydrology.

U.9.3 Predictability of Intercadal/Interannual Variability

The increased research and develop of tools to predict phenomena such as ENSO, AMO, and PDO could lead to improved long-term forecasting of hydrologic conditions for the Colorado River basin. In general, the predictability of these phenomena are limited to 9-12 months in advance with decreasing skill as lead time increases. Currently, the National Weather Service (NWS) Climate Prediction Center (CPC) provides ENSO forecasts in the form of sea surface temperatures (SSTs) for the tropical Pacific up to nine (9) months in advance (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/ensoforecast.shtml). This may assist in forecasting streamflow conditions in Lower Basin tributaries, but does not help in the forecasting of Upper Basin streamflow.

Currently, there are no publicly available tools available to forecast AMO and PDO conditions. However, researchers have noted that the PDO is a red noise process [i.e., the autocorrelation (or memory) is proportional to the size the anomaly] forced by ENSO, so the predictability of PDO would follow that of ENSO forecasts (Philip Mote, personal communication, 2007). The potential for predicting the AMO may be more promising. Griffies and Bryan (1997) and Collins and Sinha (2003) have noted that Atlantic SSTs and the thermohaline circulation have potential predictability of one to two decades into the future.

It is also important to highlight the usefulness of interannual/interdecadal variations on water resources planning with a 20-year planning horizon. The ability of a phenomenon such as AMO to persist for 10-20 years suggests that in the short term, these phases should be closely watched and corresponding hydrologic impacts evaluated. This could be just as important as evaluating the impacts of climate change that may not really be noticed in the basin for 20-50 years.

U.9.4 Relevance to Hydrologic Scenarios for Planning

As noted earlier, the hydrologic scenarios used by Reclamation for planning over a 20-50 year time period include historical streamflow data from 1906 to the present and reconstructed streamflow data from about 1500 to the present. These scenarios include all years of data and encompass all phases of ENSO, AMO and PDO. In this section, the potential of using the phase of ENSO, AMO, or PDO is demonstrated for developing hydrologic scenarios.

Figure U-28 presents the average streamflow conditions at Lees Ferry during the different phases of AMO from 1906 to the present. Evaluating the average conditions during each phase (as represented by the box plots), there appears to be a shift in the monthly streamflow values where flows are higher during an AMO negative phase and lower during an AMO positive phase. These differences are further demonstrated in Figure U-29 where the historical traces of streamflow (light gray lines) during AMO positive and AMO negative phases are presented along with the long-term monthly average (dark line). These are hydrologic scenarios that could be used for long-range outlooks for streamflow.

Lastly, the relative change in streamflow conditions during the various phases of ENSO, PDO, and AMO are important to note in the context of projected changes in streamflow under climate change scenarios. Figure U-29 presents the distribution of the median streamflow for the Upper and Lower basins during the positive and negative phases of ENSO, PDO, and AMO, along with the projected changes in streamflow for the period 2010-2039 based on output from 11 climate models and 2 different climate change scenarios (Christensen and Lettenmaier, 2006). It is noteworthy that the changes in streamflow corresponding to interannual and interdecadal climate phenomenon is comparable (if not larger) than the projected changes in streamflow under climate change scenarios.

Figure U-28
Monthly Streamflow at Lees Ferry for AMO + and AMO – Phases from 1906 to the Present

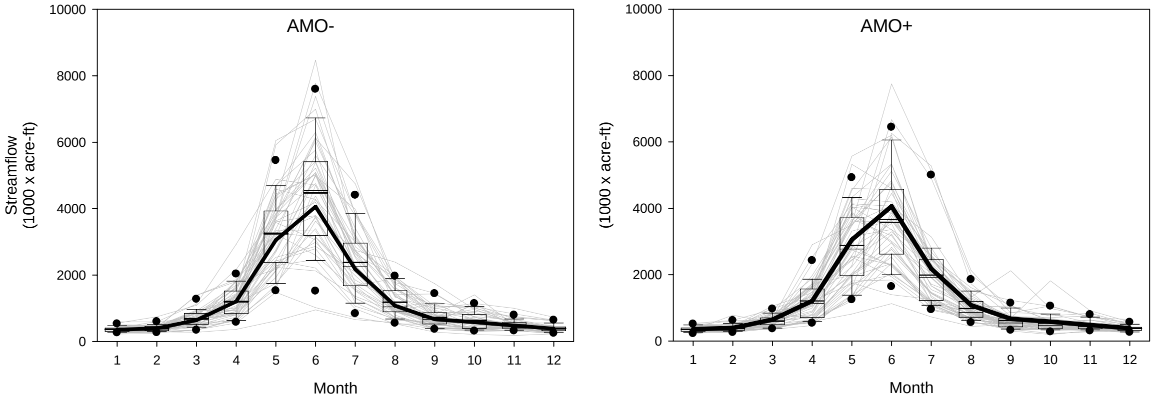
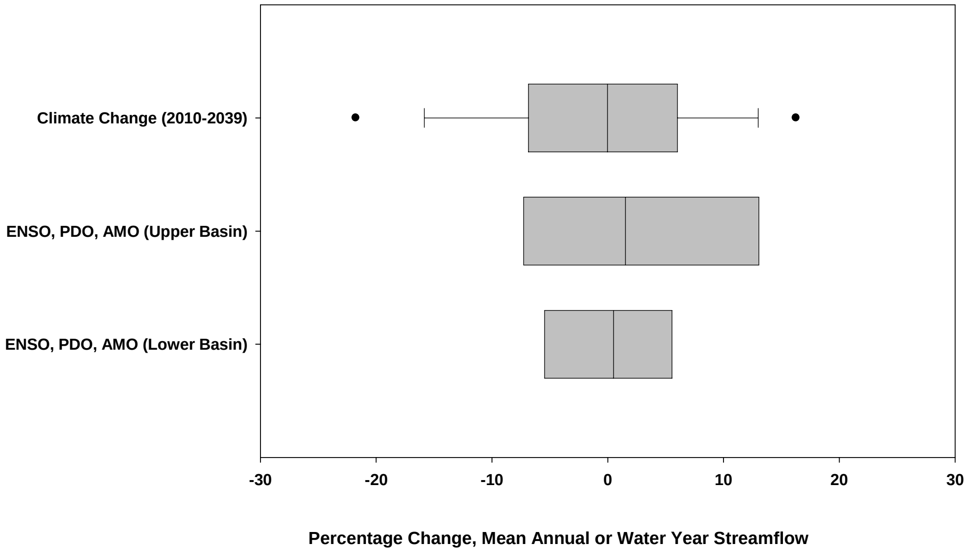


Figure U-29
Box-and-Whisker Distributions of 2010-39 Runoff Change Relative to Historical (1950-1999)
Corresponding to Various Climate Change Scenarios



The whiskers represent the 10th and 90th percentiles, the box represents the 25th and 75th percentiles, and the dots represent the outliers. In addition, distributions are provided of the runoff change during all phases (+ and -) of ENSO, PDO, and AMO for the Upper and Lower Colorado River Basin

U.10 Summary of Analysis Options and Future Needs

The information presented in this report highlight several important areas where Reclamation may use past and future climate information in the planning of water resources for the Colorado River basin.

U.10.1 Summary Points

- Climate models project that temperatures will increase globally by 1 to 2ºC in the next 20-60 years. The projections are fairly consistent for the next 20 years with a 1ºC increase, with larger uncertainty in the 40-year projections. The downscaling of global temperature increase to Colorado River Basin (CRB) climate change is less certain; however, it is expected that regional temperatures will also increase. Regional precipitation response is even less certain with comparable evidence suggesting wetter or drier conditions.

- The potential impacts of climate change on the CRB's water resources have been a subject of research for several decades. Initial studies related assumed regional climate change to region runoff response. Recent studies have been refined in several ways, including (a) how assumed climate changes are derived from global climate projections produced by various GCM simulations that reflect a range of global climate forcing scenarios, (b) how GCM output is bias-corrected and downscaled, and (c) how this output translated into region runoff response. Various analytical design options are represented by the survey of studies referenced in Section W.5 (Table U-3). Although an aggregate message from these studies may be that the *typical runoff response averaged across climate projections* spanning wetter to drier and less-warming to more-warming conditions is generally a mean annual decrease, the *range of runoff response across these same scenarios* is considerably broader and varies from increase to decrease. Note that due to advances in knowledge, technical abilities, and other factors, not all past studies retain the same significance today.

- Studies highlighted in Section W.5 show that system storage is very sensitive to changes in mean inflows as well as sequences of dry and wet years. This highlights the importance of properly investigating changes in both mean and variability in analyses of future system operations.
- Studies considered in Table U-3 feature varied treatment of projected climate *variability*, ranging from earlier studies where variability change was essentially not considered to more recent studies where GCM transient climatic conditions, bias-corrected or not, are used as input to the runoff response analysis. The significance of projected "change in climate variability" and its interaction with "change in climate norms" remains a question for research and affects ability to evaluate projected runoff uncertainty in the CRB.
- Paleoclimatic information suggests that long term average of natural flows from the upper CRB is 13.0 to 14.7 maf, compared to the gage record average of 15.2 maf. The paleoclimatic information may not necessarily represent future climate scenarios, but could be useful in framing assumed variability in future planning hydrologic sequences, with or without the joint consideration of future climate change. In particular, paleoclimate information offers evidence on drought spell potential beyond what has been experienced during the instrumental record, indicating a broader range of drought possibilities for the future.
- Interannual/interdecadal oscillation phenomena such as ENSO, PDO and/or AMO are *very significant* in the context of water resources planning within a 10- to 20-year horizon because such oscillations can persist in a given phase for a decade or longer. Evaluating the state of these oscillations and understanding their forcing mechanisms may be more important than evaluating impacts of projected climate change within a 10- to 20-year horizon.

U.10.2 Recommendations for Planning Studies

U.10.2.1 Shorter Look-Ahead Studies

For studies and management decisions involving shorter look-ahead horizons (e.g., less than 20 years), an appropriate level of analysis might involve a qualitative discussion of climate change and how interannual to decadal variability during the study's look-ahead horizon could be a more significant uncertainty than that associated with near-term projected climate change. This decision would be based on the limited projected change in climate trends over the near term and general inability to predict phase shifts in the interdecadal oscillations (e.g., AMO, PDO, etc.) that might overwhelm the trend signal during the same period. (See Figure U-29). Alternatively, if the role of shorter-term climate is critical to the study, the proposed qualitative discussion might be accompanied by a quantitative sensitivity analysis, where a range and distribution of 10- to 20-year hydrologic conditions are estimated based on instrumental record and paleoclimate evidence (in terms of mean, variance, and sequence; perhaps conditioned by understood relations with climate oscillations) and subsequently related to operations during the same look-ahead horizon.

U.10.2.2 Longer Look-Ahead Studies completed during the Near-Term

For studies and decisions concerned with greater than 20-year look-aheads and being evaluated on the near-term, it is suggested that a quantitative sensitivity analysis be conducted on operations response to projected climate change. By comparing system performance using projected climate change hydrology to historical hydrology, useful knowledge about system sensitivity should be ascertained. Given Reclamation’s current limited ability to easily simulate runoff response to climate change in the CRB, which are highlighted in Section W.9.3, near-term studies should be framed using existing projections of climate and related runoff response. For such studies addressed during the near-term, scoping of sensitivity analysis should begin with a focused consideration of available literature. Rather than try to frame the analysis on all climate change and runoff impacts studies that have been conducted for the CRB (e.g., representing all studies listed in Table U-3), it is recommended that the criteria listed in Section W.6.5 be considered when reviewing available information.

U.10.2.3 Longer Look-Ahead Studies initiated beyond the Near-Term

Recommendations from section W.9.2.1 and Section W.6.5 are still relevant for studies that may be scoped beyond the near-term. However, we recommend that research and development be pursued as described in section W.9.3 to improve Reclamation’s ability to consider and incorporate climate change information in future CRB studies. Some of the research and development can be pursued in-house, but much will need the broader assistance of scientists and engineers from the research and consulting communities.

U.10.3 Recommendations for Research and Development

- **Improved Availability and Temporal Resolution of Regional Climate Projection Datasets.** Currently, there is limited access to bias-corrected and downscaled climate projection datasets over the Colorado River basin. For example, there are more than 140 archived IPCC AR4, SRES A2, A1b, and B1 projections archived at LLNL PCMDI, compared to the 22 SRES A2 and B1 projections considered in Christensen and Lettenmaier (2006). Bias-correction and spatial downscaling procedures should be applied to the raw GCM outputs before they can be used to support regional to local hydrologic and water management impacts studies (see criteria in Section W.6.5)[9]. An archive of such data should be made available to researchers and the public. In addition, as dynamically downscaled datasets become available, these datasets should be added to the archive. Reclamation should encourage PCMDI and others to make daily and potentially sub-daily data available rather than the current monthly data which requires an additional and unnecessary temporal downscaling step for many hydrologic models.

- **Improved Ability to Model Runoff Under Climate Change.** Currently there are only a few runoff models available to generate CRB natural flow given climate inputs and Reclamation does not have easy access to these models. Reclamation needs to build internal staff expertise with available runoff model applications in the basin, and build coalitions with external groups that use such applications (e.g., working with groups familiar with UW's VIC hydrologic model, or NWSRFS). Ideally, such runoff applications would also report other hydrologic processes' response to climate change (e.g., soil moisture, evapotranspiration, groundwater interactions with surface water), which might involve development of applications that involve coupling of rainfall-runoff (e.g., NWSRFS) or land-surface model applications (e.g., VIC) with groundwater models (e.g., ModFlow). Several analytical designs (Section W.6.4) involve statistical methods that do not require runoff simulation. These methods should also be investigated by Reclamation.

- **Investigate Paradigm for Colorado River basin Precipitation Response.** While there is an evolving paradigm for how the American Southwest and other existing dry subtropical areas of the globe should respond to climate change, it is not clear how nearby relatively wet mountainous areas such as the Rockies should respond. In addition, the ability of GCMs to simulate future precipitation conditions at this spatial scale is questionable. Both the lack of a paradigm and current modeling capabilities constrain assumptions about future precipitation over the basin, and necessitate probabilistic or scenario-based approaches that explicitly recognize these uncertainties, to the extent that they might be quantified.

- **Diagnose and Improve Existing Climate Models Before Adding Additional Features.** Given known GCM limitations in simulating regional precipitation, climate research groups should focus a portion of their efforts on diagnosing and correcting biases in the current collection of IPCC AR4 AOGCMs, even though such efforts would compete for human and computational resources currently reserved for the development of new "Earth System Models" (i.e. ESMs, or AOGCMs modified to include interactive

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[9] As of Summer 2007, Reclamation has begun working with research collaborators at Lawrence Livermore National Laboratory and Santa Clara University to produce an archive of bias-corrected and downscaled IPCC AR4 climate projections. The objective is to produce archived datasets featuring monthly 20th to 21st century time-series of surface air temperature and precipitation at eighth degree spatial resolution, and with geographic coverage spanning the contiguous United States (i.e. encompassing all of Reclamation's service areas). Bias-correction and downscaling procedures are being implemented using methods featured in Maurer (2007) and Christensen and Lettenmaier (2006). This effort may partially fulfill this need, but it is uncertain.

carbon cycle, chemistry, computed aerosols, and dynamic vegetation.)[10]. There is evidence that systematic errors in AR4 AOGCMs would still be present after coupling with additional ESM components and hence waiting for ESM models to solve existing problems is unlikely to be entirely satisfactory.

- **Investigate Changes in Modeled Climate Variability at Multiple Time Scales.** It is well appreciated that the Colorado River is sensitive to changes in mean flow. However, variability as represented by drought spells, wet refill periods, and extended decadal and longer periods of above and below average flow are also critical for determining system yield. Therefore, investigation of such variability in modeled sequences of precipitation, runoff and other climatic variables is critical. While future variability may not be similar to past variability, the variability in models should be characterized and explained both in the context of the historical record and the paleo record. In addition, the ability of the current generation of GCMs and the hydrology models to reproduce the historical variability of the CRB has not been studied.

- **Improve Understanding of Surface water, Groundwater and Land cover Interaction.** Because rivers and groundwater are intimately connected, understanding the entire recharge process and its response to climate change is critical. Hence, research is required on groundwater recharge and movement at scales relevant to regional runoff analysis, and this in turn requires understanding the aggregate process of mountain block recharge and the role of riparian and root zone vegetation. The latter leads to additional research questions on how basin land cover and natural evapotranspirative demand will respond to global climate change (Section W.6.3).

- **Improve Prediction of Interdecadal Oscillations.** The predictability of interdecadal climate oscillation phases (e.g., AMO, PDO) and their associated hydrologic impacts on the Colorado River basin are not well understood. Shorter-term planning may be more influenced by phase persistence and transition among these oscillations than by projected changes in climate means. Reclamation should actively support, either materially or otherwise (i.e., through partnerships and inter- or extra-agency interactions), efforts in the science and the applications community to advance knowledge in this area (i.e., 2- to 10-year climate prediction research).

- **Investigate use of Paleo Record to Inform Modeled Streamflow Variability.** Reclamation has funded some paleo-climate research on how to use information from the paleoclimate record in modeling studies. While the past will not repeat, the paleo record contains a wealth of information on natural variability that should not be ignored. For example, there may be valuable ways of combining paleo data with modeled and or historical data to modify the variability in these sequences in useful ways.

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[10] (Jerry Meehl, 16 February 2007, presentation comments at WGNE/PCMDI Systematic Errors Workshop, 12-16 February 2007, San Francisco, CA; P. Chris Milly, 31 May 2007, personal communication)

- **Interact with Federal Climate Change Science Program and other Climate Change Research Initiatives.** Although Reclamation can pursue and fund some of the Research and Development work described above, many of these problems will require the assistance of the larger scientific and engineering community. The Department of the Interior is one of thirteen agency members of the approximately $2 billion per year federal Climate Change Science Program, the umbrella under which all federal climate change activity is pursued. In order to raise the profile of these issues and obtain resources to help solve them, Reclamation should engage the CCSP. In addition, Reclamation should collaborate with NOAA, the National Center for Atmospheric Research, and the University research community.

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Attachment 1: Climate Technical Workgroup

Invited Climate Scientists

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Marty Hoerling, NOAA
David Yates, NCAR.
Claudi Tebaldi, NCAR
Kelly Redmond, Desert Research Institute.
Jonathan Overpeck, University of Arizona
Dan Cayan, Scripps Institute of Oceanography
Kevin Trenberth, NCAR
Dennis Lettenmaier, University of Washington
Tom Piechota, University of Nevada, Las Vegas
Randall Dole, NOAA
Phil Mote, University of Washington

Climate Meeting (November 8, 2006) Attendees

Climate Scientists
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Tom Piechota
Randall Dole

USBR
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Attachment 2: Glossary of Terms

Abrupt climate change: The nonlinearity of the climate system may lead to abrupt climate change, sometimes called rapid climate change, abrupt events or even surprises. The term abrupt often refers to time scales faster than the typical time scale of the responsible forcing. However, not all abrupt climate changes need be externally forced. Some possible abrupt events that have been proposed include a dramatic reorganization of the thermohaline circulation, rapid deglaciation and massive melting of permafrost or increases in soil respiration leading to fast changes in the carbon cycle. Others may be truly unexpected, resulting from a strong, rapidly changing forcing of a nonlinear system.

Atlantic Multi-Decadal Oscillation (AMO): The Atlantic Multi-Decadal Oscillation (AMO) is defined as the leading mode of low frequency, North Atlantic Ocean (0 to 70o) sea surface temperature (SST) variability with a periodicity of 65 to 80 years.

Analogue (or Analogs): Two observed states of the atmosphere that are very close by some measure, also applies to states of a model. Formal measures of closeness include anomaly correlation, root-mean-square distance, and covariance. Usually one expects analogs to occur only during the same time of year. Atmospheric analogs that are close compared to current levels of observational error are unlikely to be found unless one studies a single variable confined to a very small area, or otherwise reduced the degrees of freedom to a very small number.

Anthropogenic: Resulting from or produced by human beings.

Anthropogenic forcing: *Radiative* forcing resulting from or produced by human beings.

Atmosphere-Ocean General Circulation Model (AOGCM): Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. These models simulate atmosphere and ocean circulation and their interactions with each other, land, and cryospheric processes. Simulations are forced by several factors, including time series assumptions on atmospheric greenhouse gas and aerosol concentrations.

Baseflow: The sustained low flow of a stream, usually groundwater inflow to the stream channel.

Beneficial use: A use of water resulting in appreciable gain or benefit to the user, consistent with state law, which varies from one state to another.

Climate: Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. It is typically characterized in terms of suitable averages of the climate system over periods of a month or more, taking into consideration the variability in time of these averaged quantities. The relevant quantities are most often surface variables such as temperature, precipitation and wind.

Climatic classifications include the spatial variation of these time-averaged variables. Climate in a wider sense is the state, including a statistical description, of the climate system. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate had broadened and evolved in recent decades in response to the increased understanding of the underlying processes that determine climate and its variability.

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also *Climate variability*.

Climate Model: A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or *anthropogenic* or external *forcing* (external variability). See also *Climate change*.

Colorado River basin: The drainage basin of the Colorado River in the United States. The Colorado River watershed area encompasses over 246,000 square miles and is a primary water supply for residents in seven states including Colorado, Utah, Wyoming, New Mexico, Arizona, Nevada, and California.

Colorado River Compact: The Colorado River Compact is a 1922 agreement among seven U.S. states in the basin of the Colorado River in the American Southwest governing the allocation of the river's water. The compact divides the river basin into two areas, the Upper Basin (comprising Colorado, New Mexico, Utah and Wyoming) and the Lower Basin (Nevada, Arizona and California). The compact requires the Upper Basin states to deliver water at a rate of 7.5 million acre feet per year averaged over a moving ten-year average.

Colorado River Simulation System (CRSS): An operational model of the Colorado River system based on a monthly timestep. CRSS is a simulation model consisting of a database and a modeling code. The database describes the physical configuration of the natural and man-made features of the Colorado River system, the operating rules for the man-made features, the natural gains and losses of water that enter and leave the system, and the water used by or requested for use for human activities. The modeling code simulates the physical processes and institutional drivers that determine the system conditions, according to the data contained in the database.

Compact deliveries: Water allocations, diversions, and deliveries mandated under the Colorado River Compact of 1922.

Confidence: The level of confidence in the correctness of a result is expressed using probability confidence intervals.

Decadal: Occurring over a 10-year period.

Dendrochronology: The analysis of the annual growth rings of trees, leading to the calculation of significant indices of climate and general chronology of the past. The width of a tree-ring is determined by the temperature and/or moisture that prevailed during the year of its formation. Since stress from temperature and/or moisture variations reduces the width of the seasonal growth of a tree ring, dendrochronology has important application in the study of long-term climatic variations.

Domestic use: Also called residential water use or domestic withdrawals. Water used for household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and water lawns and gardens. The water may be obtained from a public supply or may be self-supplied.

Direct Natural Flow Record (DNF): The Index Sequential Method (ISM) applied to the 1906 to 2004 Colorado River natural flow record.

Downscaling techniques: Techniques to generate climate scenarios at a point or watershed based on climate scenarios produced by global climate models at a larger spatial scale.

> **Bias-correction:** Simulations or forecasts of climate from dynamical models do not always correspond to reality (i.e., observations), thus, resulting in 'bias'. There are statistical methods to correct this and often referred to as 'bias correction' tools. Typically, they involve fitting a statistical model between the dynamical model simulations and the observations over a period. The fitted regression is used to correct future model simulations.
>
> **Disaggregation:** Breaking down a single indicator into subgroups variables. In section W.4 of this report, disaggregation is the second component of a downscaling technique where 2-degree lat-long climate projections are disaggregated into 1/8 degree projection data; and the second method, streamflow at an aggregate gauge (usually a gauge at the downstream) is disaggregated (or split) to flows at several upstream gauges - such that

the disaggregated flows add up to the flow at the aggregate gauge.(This enables the simulation of flow scenarios at all the required gauges in a parsimonious manner).

Drought: A period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore any discussion in terms or precipitation deficit must refer to the particular precipitation-related activity on a regional or continental scale.

Earth System Model (ESM): Models based on AOGCM (with various levels of simplification) that also include interactive carbon cycle, chemistry, computed aerosols, and dynamic vegetation. Earth System Models of Intermediate Complexity (EMIC) are discussed in the IPCC AR4 report from Working Group I, and are described as "reduced-resolution models that incorporate most of the processes represented by AOGCMs, albeit in a more parameterized form. They explicitly simulate the interactions between various components of the climate system. Similar to AOGCMs, but in contrast to simple climate models, the number of degrees of freedom of an EMIC exceeds the number of adjustable parameters by several orders of magnitude. ... like simple climate models, EMICs can explore the parameter space with some completeness and are thus appropriate for assessing uncertainty."

Empirical: Relying upon or derived from observation or experiment; Based on experimental data, not on a theory.

ENSO: A contraction of names of two phenomena that were recognized to be different expressions of the same process: “El Niño” refers to anomalous strong warming of the surface waters of the eastern equatorial Pacific Ocean, while “Southern Oscillation” refers to concurrent changes in surface barometric pressure in the tropical Pacific. The ENSO phenomenon is now understood to span the equatorial Pacific and to have opposite phases with a 2-7 year periodicity, and with impacts that occur in various parts of the world. The warm phase of ENSO is called El Niño, while the cold phase is called La Niña (Philander 1990). Common indices used to describe ENSO conditions include the Southern Oscillation Index (SOI), equatorial Pacific sea surface temperatures (e.g., NINO12, NINO3) and the Multivariate ENSO index (MEI).

Evapotranspiration: 1. The combined process through which water is transferred to the atmosphere from open water and ice surfaces, bare soil, and vegetation that make up the earth’s surface. 2. (Also called flyoff, water loss, total evaporation.) The total amount of water transferred from the earth to the atmosphere. This is the most general term for the result of this composite process; duty of water and consumptive use has more specific applications.

General Circulation Models (GCMs): *see climate model.*

Green house gases: Those gases, such as water vapor, carbon dioxide, ozone, methane, nitrous oxide, and chlorofluorocarbons, that are fairly transparent to the short wavelengths of solar radiation but efficient at absorbing the lower wavelengths of the infrared radiation emitted by the earth and atmosphere. The trapping of heat by these gases controls the earth’s surface temperature despite their presence in only trace concentrations in the atmosphere. Anthropogenic emissions are important additional sources for all except water vapor. Water vapor, the most important greenhouse gas, is thought to increases in concentration in response to increased concentrations of the other greenhouse gases as a result of feedbacks in the climate system.

Groundwater: Subsurface water that occupies the zone of saturation; thus, only the water below the water table, as distinguished from interflow and soil moisture.

Hydro-Climate Data Network (HCDN): USGS streamgages minimally affected by anthropogenic regulation or effects with sufficient periods of record.

Hydrology: The scientific study of the waters of the earth, especially with relation to the effects of precipitation and evaporation upon the occurrence and character of water in streams, lakes, and on or below the land surface.

Impaired inflows: In contrast to natural flows, these are reservoir or water system inflows affected by an upstream combination of natural runoff, human use, diversion, management, and/or allocation.

Indexed Sequential Method (ISM): A block bootstrap approach to resample a historic streamflow record. ISM cycles through each year in the natural flow record and extracts a sequence of flows beginning at that year and extending through the desired scenario length.

Inflow points: A specific location in which water flows into a body of water expressed in acre-feet per day or cubic feet per second.

Interim: Belonging to, serving during, or taking place during an intermediate interval of time; temporary: an interim agreement.

Interim shortage agreement: An interim shortage agreement in the context of this report is temporary operational guidelines for coordinated operation of Lakes Powell and Mead during times of shortage on the Colorado River.

Interpolation: The estimation of unknown intermediate values from known discrete values of a dependent variable.

IPCC: The Intergovernmental Panel on Climate Change (IPCC) established by World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) provides an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature in regular time intervals.

IPCC Fourth Assessment Report: The Fourth Assessment Report "Climate Change 2007", also referred to as AR4 is a series of reports by the IPCC and provides an assessment of the current state of knowledge on climate change including the scientific aspects of climate change, impacts and vulnerabilities of human, natural, and managed systems, and adaptation and mitigation strategies.

Jet stream: Relatively strong winds concentrated within a narrow stream in the atmosphere. While this term may be applied to any such stream regards of direction (including vertical), it is coming more and more to mean only a quasi-horizontal jet stream of maximum winds embedded in the midlatitude westerlies, and concentrated in the high troposphere. Currently, in the analysis of upper-level charts, a jet stream is indicated wherever it is reliably determined that the wind speed equals or exceeds 50 knots.

Law of the River: The water law and appropriation requirements on the Colorado River mainstem and its tributaries.

Lees Ferry: A reference point in the Colorado River 1 mile below the mouth of the Paria River in Arizona which marks the Upper/Lower Colorado River Basins. Lees Ferry is the site of the USGS stream gage above the Paria River confluence.

Linear regression: Method dealing with a straight-line relationship between variables. It is in the form of $y = a + bx$, whereas nonlinear regression involves curvilinear relationships such as exponential and quadratic functions.

Long-wave radiation: In meteorology, a term used loosely to distinguish radiation at wavelengths longer than about 4 µm, usually of terrestrial origin, from those at shorter wavelengths (shortwave radiation), usually of solar origin.

Lower Basin: The part of the Colorado River watershed below Lees Ferry, Arizona; covers parts of Arizona, California, Nevada, New Mexico and Utah.

Million acre-feet (maf). The volume of water that would cover 1 million acres to a depth of 1 foot.

North Atlantic Oscillation (NAO): NAO is an oscillation of pressure differences between the subtropical high-pressure system located in the tropical Atlantic near the Azores and the subpolar low-pressure system located near Iceland (Hurrell, 1995). The difference in surface pressure generally influences the surface winds and the steering of storms from west to east. The NAO has quasi-biennial and quasi-decadal periodicity (Hurrell and Van Loon, 1997).

National Environmental Policy Act (NEPA): The National Environmental Policy Act (NEPA) requires federal agencies to integrate environmental values into their decision making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. To meet this requirement, federal agencies prepare a detailed statement known as an Environmental Impact Statement (EIS). EPA reviews and comments on EISs prepared by other federal agencies, maintain a national filing system for all EISs, and assures that its own actions comply with NEPA.

Natural inflows: Inflows absent of any human use, diversion, management, or allocation; also called virgin flows.

Nonparametric: Problems for which a distribution curve cannot be drawn, either because the parameters of the equation are not known, or because there is no equation at all.

North American Monsoon: The North American monsoon (NA monsoon), variously known as the Southwest United States monsoon, the Mexican monsoon, or the Arizona monsoon, is experienced as a pronounced increase in rainfall from an extremely dry June to a rainy July over large areas of the southwestern United States and northwestern Mexico. These summer rains typically last until mid-September when a drier regime is reestablished over the region. Geographically, the NA monsoon precipitation region is centered over the Sierra Madre Occidental in the Mexican states of Sinaloa, Durango, Sonora and Chihuahua. The regime extends northward into the Arizona, New Mexico and Colorado. Typically, the NA Monsoon region is defined by sites that receive at least 50% of its annual precipitation in July, August and September.

Outflows: The amount of water passing a given point downstream of a structure, expressed in acre-feet per day or cubic feet per second. Water flowing out of a body of water.

Paleo-climate (or "Paleo"): Climate for periods prior to the development of measuring instruments, including historic and geologic time, for which only proxy climate records are available. (Paleoclimatolgoy: The study of past climate throughout geologic and historic time (paleoclimates), and the causes of their variations.

Paleo streamflow reconstruction: Using analyses from tree-ring reconstructions, streamflow volumes prior to the gage record can be estimated using a statistical model, which captures the relationship between tree growth and the gage record during their period of overlap. Then, this model is applied to the tree-ring data for the period prior to the gage record.

Palmer Drought Severity Index (PDSI): An index formulated by Palmer (1965) that compares the actual amount of precipitation received in an area during a specified period with the normal or average amount expected during that same period. The PDSI is based on a procedure of hydrologic or water balance account by which excesses or deficiencies in moisture are determined in relation to average climatic values. Values taken into account in the calculation of the index include precipitation, potential and actual evapotranspiration, infiltration, of water into a given soil zone, and runoff. This index builds on Thornthwaite's work (1931, 1948), adding 1) soil depth zones to better represent regional change in soil water-holding capacity; and 2) movement between soil zones and, hence, plant moisture stress, that is, too wet or too dry.

Parts per million, ppm: Parts per million ("ppm") denotes one particle of a given substance for every 999,999 other particles.

Pacific Decadal Oscillation (PDO): The Pacific Decadal Oscillation (PDO) is a pattern of ocean variability in the North Pacific that is similar to ENSO in some respects, but has a much longer cycle (20 - 50 year) (Mantua et al., 1997, Mantua and Hare, 2002). Specifically, it is defined as the standardized difference between sea surface temperatures (SSTs) in the north-central Pacific and Gulf of Alaska.

Pacific North American pattern (PNA): The Pacific North America pattern (PNA) is one of the largest-scale ocean-atmosphere patterns that vary on seasonal, interannual, and interdecadal time scales. The PNA is a measure of atmospheric pressure anomalies at four locations in the northern hemisphere (Horel and Wallace 1981). The pressure near the Aleutian Islands and the southeastern U.S. have the same sign pressure anomaly, and the pressure near Hawaii and central Canada have the opposite sign pressure anomaly. The PNA index is a standardized measure of these pressure differences and is most pronounced in the winter and disappears in the summer months of June and July.

Present Perfected Rights: A water right to which the owner has applied for and obtained a permit, has complied with the conditions of the permit, and has obtained a license or certificate of appropriation. In the context of the Colorado River Compact (Compact), under Article VIII, “present perfected rights” refers to established beneficial use water rights prior to the Compact that will not be impaired.

Climate Projection: A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/ radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized and are therefore subject to substantial uncertainty.

Quantile: A generic term for any fraction that divides a collection of observations arranged in order of magnitude into two specific parts.

Return flows: The water that reaches a ground or surface water source after release from the point of use and thus becomes available for further use; water that re-enters the water system used further downstream.

Radiative forcing: In radiation, the net flux of radiation into or out of a system. As a consequence of radiative forcing there must be some change to the nonradiative energy states of the system (e.g., its temperature may change).

Rim inflows: Flows at the upper most gauges of tributaries and also the main stem.

Riparian: Of, on, or pertaining to the bank of a river, pond, or lake.

Scenario (Climate Scenario): A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Shortage: In a given watershed, a water supply deficit attributed to below average streamflow volumes due to natural or managerial attributions.

SNOTEL: Abbreviation for SNOwpack TELemetry. A west-wide system for obtaining snow water equivalent, precipitation, air temperature, and other hydrologic measurements from remote data sites via radio transmission.

SNOW17 snowmelt model: The SNOU-17 model is one of operations available in the National Weather Service River Forecast System (NWSRFS). It is a conceptual model in which each of the significant physical processes affecting snow accumulation and snowmelt is mathematically represented. The model uses air temperature as the sole index to energy exchange across the snoU-air interface and was developed to run in conjunction with a rainfall-runoff model. Developed by Anderson, (1973), (1976).

SnoU-water equivalent (SWE): The amount of water contained within the snowpack. It can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously.

SRES scenarios: SRES scenarios are emission scenarios developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the climate projections shown in Chapter 10 of this report. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

> **Scenario family:** Scenarios that have a similar demographic, societal, economic and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1 and B2.
>
> **Illustrative Scenario:** A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised scenario markers for the scenario groups A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.
>
> **Marker Scenario:** A scenario that was originally posted in draft form on the SRES website to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the closest scrutiny of the entire writing team and via the SRES open process. Scenarios were also selected to illustrate the other two scenario groups.
>
> **Storyline:** A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.

Static: Fixed; stationary.

Stochastic hydrology: The science that pertains to the probabilistic description and modeling of the value of hydrologic phenomena, particularly the dynamic behavior and the statistical analysis of records of such phenomena.

Storage: The retention of water or delay of runoff either by planned operation, as in a reservoir, or by temporary filling of overflow areas, as in the progression of a flood wave through a natural stream channel.

r2: Statistical measure of how well a regression line approximates real data points; an r-squared of 1.0 (100%) indicates a perfect fit.

Temporal: Of, relating to, or limited by time, i.e. temporal boundaries.

Trajectories: see projection

Trigger: Procedure that is automatically executed in response to certain threshold events; event-driven programming.

Upper Basin: The part of the Colorado River watershed above Lees Ferry, Arizona; that covers parts of Arizona, Colorado, New Mexico, Utah and Wyoming.

Variable Infiltration Capacity (VIC) Model: VIC is a macroscale hydrologic model that solves full water and energy balances. VIC is a research model and in its various forms it has been applied to many watersheds including the Columbia River, the Ohio River, the Arkansas-Red Rivers, and the Upper Mississippi Rivers, as well as being applied globally.

Water balance (Water budget): An analytical tool whereby the sum of the system inflows equals the sum of the system outflows. A summation of inputs, outputs, and net changes to a particular water resource system over a fixed period.

Watershed: All the land and water within the confines of a certain water drainage area; the total area drained by a river and its tributaries.

Water supply: Process or activity by which a given amount of water is provided for some use, e.g., municipal, industrial, and agricultural.

Water year: A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30, and is designated by the year in which it ends.