RECLAMATION
Managing Water in the West

Interim Report No. 1

Colorado River Basin Water Supply and Demand Study

Technical Report B – Water Supply Assessment

U.S. Department of the Interior
Bureau of Reclamation

June 2011

Mission Statements

Protecting America's Great Outdoors and Powering Our Future
The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Colorado River Basin Water Supply and Demand Study

Technical Report B – Water Supply Assessment

Prepared by:

Colorado River Basin Water Supply and Demand Study Study Team

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Bureau of Reclamation

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1.0 Introduction

The Plan of Study, provided in Appendix 1 of the *Status Report*, states that the purpose of the Colorado River Basin Water Supply and Demand Study (Study) is to conduct a comprehensive study to define current and future imbalances in water supply and demand in the Colorado River Basin (Basin) and the adjacent areas of the seven Colorado River Basin States[1] (Basin States) that receive Colorado River water over the next 50 years, and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Study contains four major elements to accomplish this goal: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Opportunities for Balancing Supply and Demand.

The purpose of this Water Supply Assessment phase is to determine the probable magnitude and variability of historical and future natural flows in the Basin. Natural flow represents the flow that would have occurred at a location, had depletions and reservoir regulation not been present upstream of that location.

Because the magnitude and variability of the future water supply is uncertain, a set of future water supply scenarios has been developed to capture the uncertainty, including the potential effects of future climate variability and climate change. The water supply projections will be used to analyze future reliability of the river system to meet water demands, with and without future adaptation and mitigation strategies. The water supply assessment draws on the expertise of researchers and analysts worldwide who have been investigating the hydrology of the Colorado River Basin and the dynamics of global climate change.

This report presents the findings as of January 31, 2011, on the development of water supply projections to be used in the Study. Included are explanations of the process of developing future scenarios affecting water supply, the methods of assessing future water supply information for the scenarios, and the quantification of future supply under each of the supply scenarios.

2.0 Approach to Water Supply Scenario Development

A scenario planning process was implemented to examine the uncertainty in future water supply and demand and is detailed in *Technical Report A - Scenario Development*. As noted in that report, a collaborative process that engages stakeholders is essential to the successful development of future scenarios. For this Water Supply Assessment, numerous organizations have participated, including representatives of Bureau of Reclamation (Reclamation), Reclamation's Technical Service Center, the Basin States, U.S. Fish and Wildlife Service, National Oceanic and Atmospheric Administration (NOAA), Native American tribes and communities, environmental organizations, and others interested in the Basin. To date, this

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[1] Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming

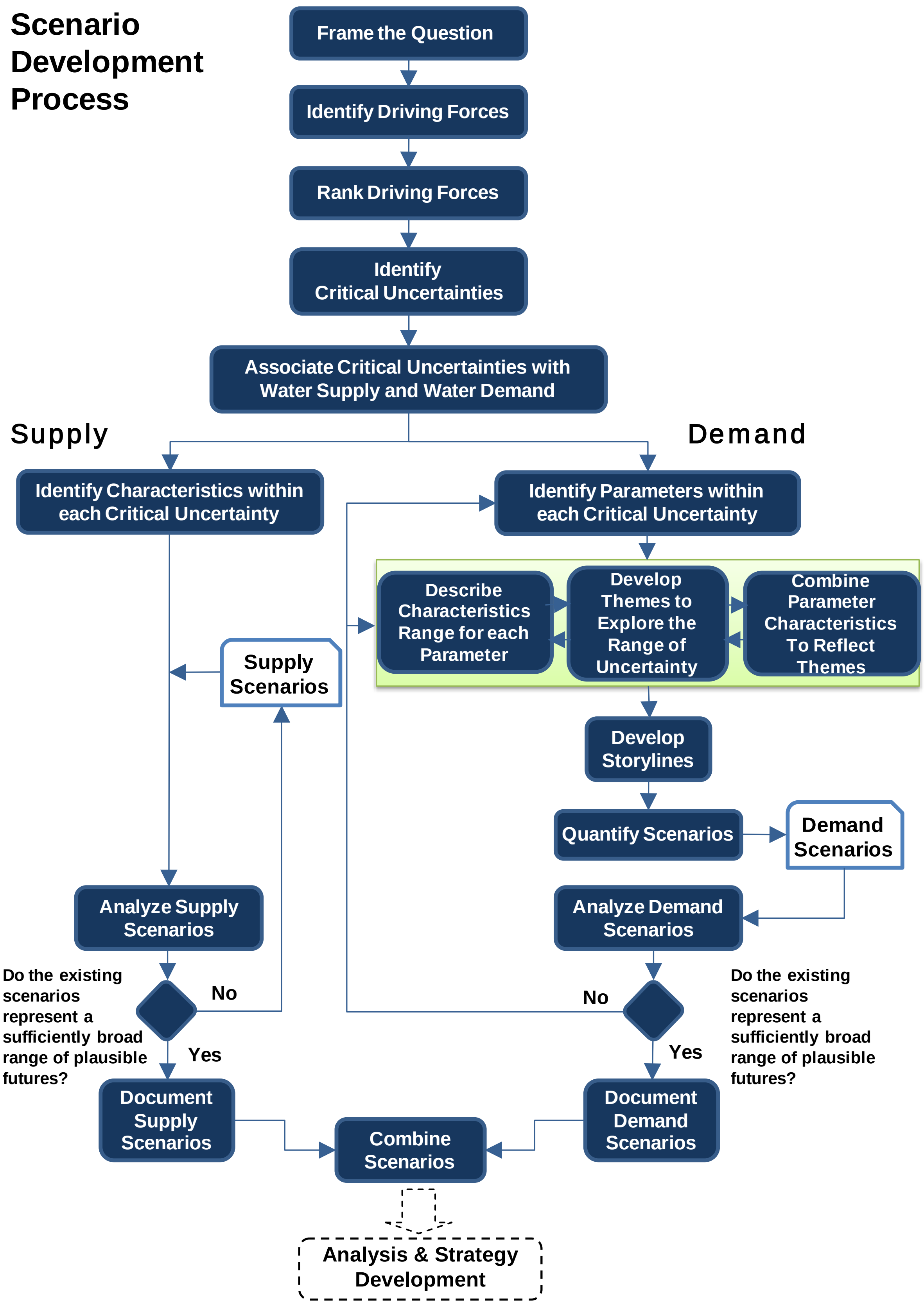
collaboration has been accomplished through a variety of means, including participation in a Water Supply Sub-Team and direct contact with the organizations listed above. The Water Supply Sub-Team members and the points of contact are provided in Appendix B1 of this report.

A scenario is an alternative view of how the future might unfold. Scenarios are not predictions or forecasts of the future. The scenario planning process involved the identification of the key driving forces (i.e., the factors that will likely have the greatest influence on the future state of the system and thereby the performance of the system over time), ranking of the driving forces as to their relative importance and relative uncertainty, and associating the highly uncertain and highly important driving forces, identified as critical uncertainties, with either water supply or water demand. The process is shown graphically in Figure B-1, which is also presented in *Technical Report A - Scenario Development*. The critical uncertainties that were identified and associated with water supply (the step "Associate Critical Uncertainties with Water Supply and Demand" in Figure B-1) are:

- Changes in streamflow variability and trends
- Changes in climate variability and trends

See *Technical Report C – Water Demand Assessment* for a discussion of the critical uncertainties associated with water demand.

FIGURE B-1
Scenario Development Process



The subsequent process (shown on the left-hand side of Figure B-1 and labeled “Supply”) was used by the Water Supply Sub-Team to move from the critical uncertainties to supply scenarios. Each step of this process is described in the following sub-sections.

Identify Characteristics within each Critical Uncertainty

Characteristics can be either qualitative or quantitative descriptions of the trend or values over time that describe the trajectory of the critical uncertainty. In 2004, Reclamation initiated a multi-faceted research and development program to enable the use of methods beyond those that use the observed record for projecting possible future inflow sequences for Colorado River Basin planning studies. Through this effort, two additional water supply scenarios were developed and have been used in previous Colorado River Basin planning studies; these scenarios assume characteristics of the water supply critical uncertainties are represented by the observed and paleo-reconstructed streamflow records. These scenarios have most recently been published in the Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement (Interim Guidelines Final EIS, Reclamation, 2007, Appendix N).

For purposes of the Study, it was determined that these previously utilized scenarios did not represent a sufficiently broad range of plausible futures as they did not include the consideration of changing climate beyond what has occurred in history. As such, a fourth scenario was developed that assumes the characteristics of the critical uncertainties, “changes in streamflow variability and trends” and “changes in climate variability and trends,” are indicated by downscaled Global Climate Model (GCM) projections.

Water Supply Scenarios

The following scenarios and associated themes are being considered in the Study:

- **Observed Record Trends and Variability (Observed Resampled):** future hydrologic trends and variability are similar to the past approximately100 years
- **Paleo Record Trends and Variability (Paleo Resampled):** future hydrologic trends and variability are represented by reconstructions of streamflow for a much longer period in the past (nearly 1,250 years) that show expanded variability
- **Observed Record Trends and Increased Variability (Paleo Conditioned):** future hydrologic trends and variability are represented by a blend of the wet-dry states of the longer paleo-reconstructed period (nearly 1,250 years), but magnitudes are more similar to the observed period (about 100 years)
- **Downscaled GCM Projected Trends and Variability (Downscaled GCM Projected):** future climate will continue to warm with regional precipitation and temperature trends represented through an ensemble of future downscaled GCM projections

The scenarios each represent a plausible future of water supply conditions. The Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios utilize approaches previously developed to represent a range of hydroclimatic variability (annual to decadal scales) under a broad retrospective view. Future changes in climate variability and trends, and their influence on streamflow and Colorado River Basin water supply, have been studied by several researchers in recent years. The Study represents the first time future climate scenarios have been included in Reclamation’s Colorado River Basin planning studies. For these reasons, greater detail is provided for the Downscaled GCM Projected scenario in this report. However, each of the scenarios in the Study represents a plausible future condition and is informative for future Colorado River Basin planning.

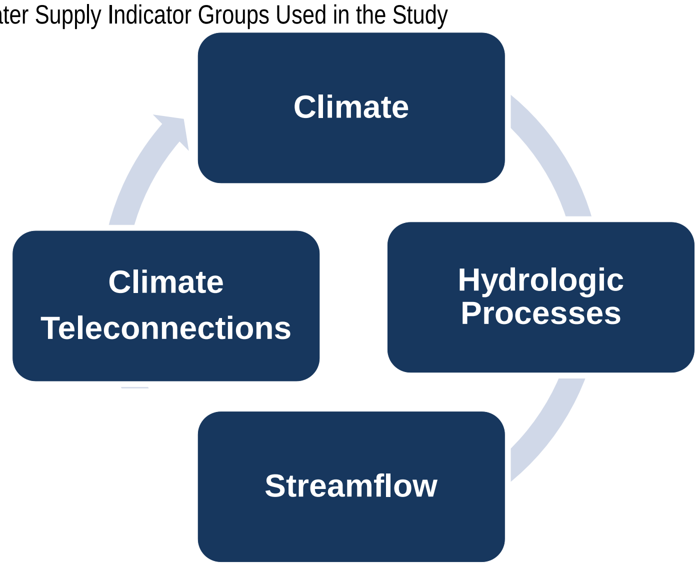
3.0 Summary of the Water Supply Assessment Approach

A plausible range of future water supply scenarios, sufficiently broad to capture the significant uncertainty of the estimates, must be considered to analyze the future reliability of the system. An assessment of historical supply conditions was performed to facilitate an understanding of how the future supply conditions projected to occur under each scenario differ from historical supply conditions. This section describes the water supply indicator groups analyzed for historical and future conditions and also includes a summary of published research related to Basin supply.

3.1 Tools and Methods

The assessment of historical and future supply conditions focused on four main groups of water supply indicators, presented in Figure B-2. The water supply indicator groups are inter-related: climate influences hydrologic processes, hydrologic processes generate streamflow, and teleconnections (defined below) influence the oscillation of climate patterns.

FIGURE B-2
Water Supply Indicator Groups Used in the Study



While the primary indicator of water supply in the Basin is streamflow, a fundamental understanding of the processes that influence the quantity, location, and timing of streamflow is beneficial. Comparisons for each indicator group are made between historical supply and future supply under the Downscaled GCM Projected scenario, as this scenario assumes a changing climate. For the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios, which assume a climate similar to the past, streamflow is the primary indicator. Methods applied to project streamflow under the future supply scenarios are described in their respective sections.

Climate indicators considered in this assessment are temperature and precipitation. Hydrologic process indicators are runoff, evapotranspiration (ET), snowpack accumulation (snow water equivalent, or SWE), and soil moisture. Climate and hydrologic process indicators were primarily derived from gridded data sets and spatial averaging was performed for selected sub-basins. The sub-basin averaging of climate and hydrologic process information allows assessment of broader regions of the Basin than the detailed grid-cell calculations.

Climate teleconnection indicators are El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO) indices. Teleconnections refer to the linkage between large-scale, ocean-atmosphere patterns (e.g., ENSO, PDO, AMO, etc.) and weather or climate changes within a separate region of the globe (e.g., precipitation patterns in the Colorado River Basin). Finally, streamflow indicators are natural flows at select locations in the Basin.

Natural flow represents the flow that would have occurred at the location had depletions and reservoir regulation not been present upstream of that location. Natural flow is computed historically by Reclamation[2] and is currently available for 29 locations throughout the Basin: 20 locations in the Upper Basin upstream of and including the Lees Ferry gaging station in Arizona, and nine additional locations below Lees Ferry, including the Paria River and other inflow points in the Lower Basin. These locations are shown in Figure B-3. At this time, the natural flow record extends from 1906 through 2008[3]. Although all gages were not in place back to 1906, the existing records were extended back to 1906 using methods described in Lee et al., 2006.

For some tributaries in the Lower Basin (specifically the Little Colorado River, Virgin River, and Bill Williams River), U.S. Geological Survey (USGS) gaged flows at specific locations near the confluence of the tributary and the Colorado River mainstream have been used. This approach is also taken for the Paria River which joins the Colorado River just downstream of Lees Ferry. In addition, the Gila River is not included in the Colorado River Simulation System (CRSS) and is therefore not included in the 29 locations where natural flow is estimated throughout the Basin. See *Technical Report C – Water Demand Assessment* and Appendix C5 for further discussion.

CRSS is Reclamation's primary Basin-wide simulation model used for long-term planning studies and in its current configuration, requires natural flow inputs at these locations on a monthly time-step over the planning horizon of the Study. Specific methodologies associated with the water supply scenarios considered in the report were used to project the future natural inflows necessary at these 29 locations.

Additional information related to individual water supply indicators, their relevance to water supply, and methods of analysis are included in Appendix B2.

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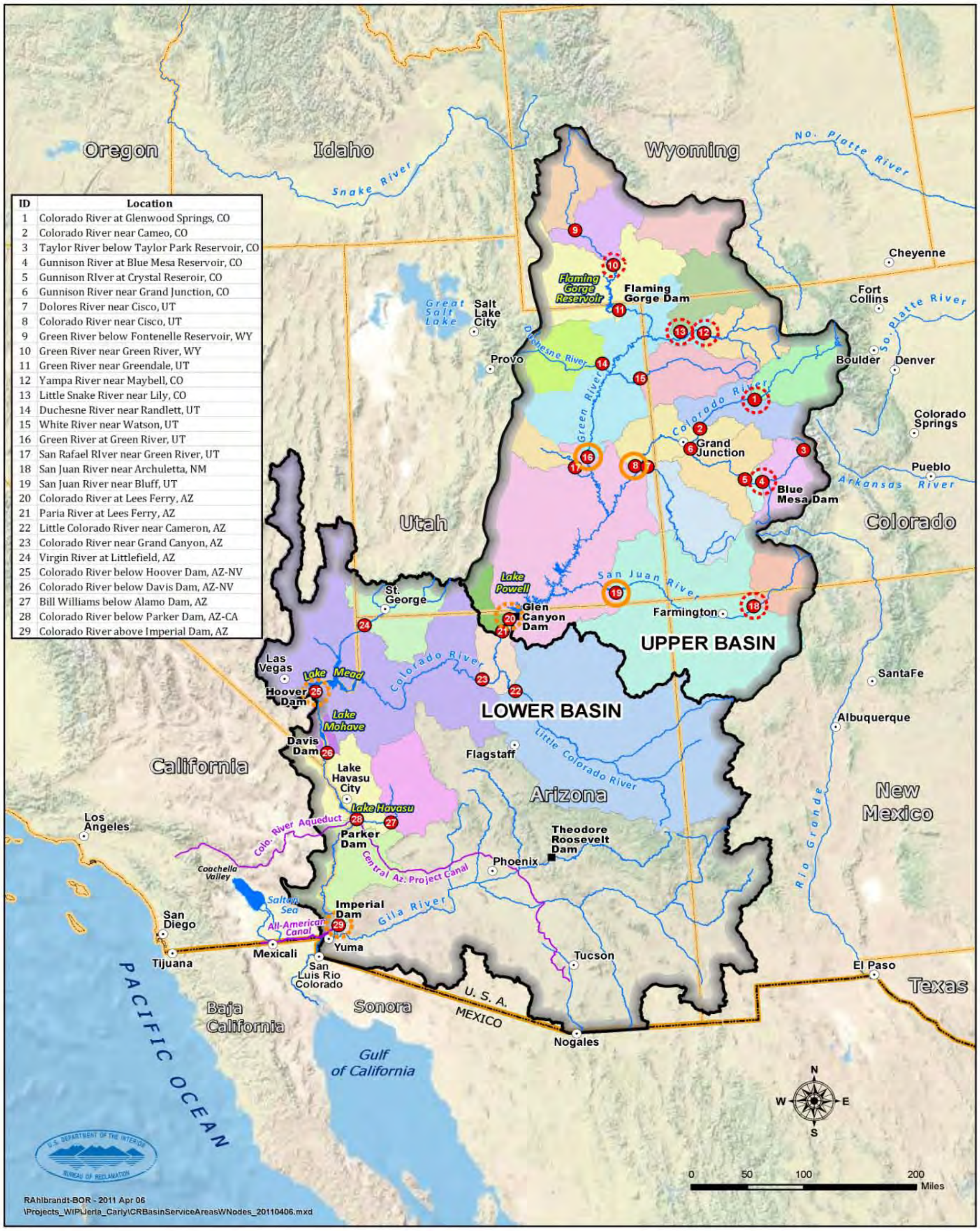
[2] Additional information, documentation, and the natural flow data are available at http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html.

[3] At the time the analysis for this report was performed natural flow data were available only through 2007.

FIGURE B-3
Colorado River Basin and 29 Natural Flow Locations (Source: Reclamation 2011)
(Circled stations have been assessed in this report; dashed circles are used to describe climate, while solid circled stations are used to describe streamflows).



3.2 Sources of Data and Information

An extensive review of relevant literature, water supply studies, and hydroclimatic data was performed as part of the Water Supply Assessment. The Colorado River Basin supply has been studied by numerous researchers and a wealth of information is available on which to build from, including several recent studies directly relevant to the Study. Relevant hydroclimate data were collected throughout the development of the process, with particular emphasis on gridded climate data sets and natural flows for the 29 natural flow locations in the Basin.

3.2.1 Literature Review

Due to its strategic importance as a source of water for the western United States, the Colorado River is one of the most studied river systems in the world. The Colorado River Basin water supply has been assessed by a variety of hydrologic analyses for many decades, but efforts have accelerated in the 1990s with the availability of general circulation models (GCM) and observed increased streamflow variability (Pagano and Garen, 2005). Reclamation published an extensive literature review of Colorado River climate and hydrology studies in Appendix U of the Interim Guidelines Final EIS. This appendix provides a summary of the state of the science in 2007. In 2011, Reclamation's Technical Service Center published a second edition of the Literature Synthesis on Climate Change Implications for Water and Environmental Resources (Reclamation, 2011) that summarized relevant research through the summer of 2010. Provided here is a brief summary of past efforts and research to assess Basin supply.

The following studies: Gleick, 1987; Lettenmaier et al., 1992; Nash and Gleick, 1991, 1993; Hamlet and Lettenmaier, 1999; McCabe and Hay, 1995; McCabe and Wolock, 1999; Wilby et al., 1999; and Wolock and McCabe, 1999, discuss climate change impacts on hydrology and water resources of western U.S. river basins. All these studies have assumed or predicted increasing temperatures, but have disagreed upon both the magnitude and direction of precipitation changes.

Nash and Gleick, 1991, evaluated prescribed changes of +2 degrees Celsius (°C) and +4°C, coupled with precipitation reductions of 10 and 20 percent. The 2°C increase/10 percent precipitation decrease resulted in a 20 percent streamflow reduction, while the 4°C increase/20 percent precipitation decrease resulted in a 30 percent runoff decrease.

Christensen et al., 2004, projected average projected temperature changes of 1.0°C, 1.7°C, and 2.4°C, and precipitation changes of 3, 6, and 3 percent for the Basin for periods 2010 to 2039, 2040 to 2069, and 2070 to 2099, respectively, relative to 1950 to 1999 means. The temperature and precipitation changes led to reductions of April 1 SWE of 24, 29, and 30 percent, and runoff reductions of 14, 18, and 17 percent for the three periods.

Updated analyses by Christensen and Lettenmaier, 2007, using a larger ensemble of climate projections, resulted in smaller projected reductions in Lees Ferry flows (less than 11 percent).

Hoerling et al., 2009, in an attempt to reconcile streamflow estimates by several researchers, summarized the recent hydroclimatic analyses of the Colorado River Basin and found that the projections ranged from 5 to 20 percent reduction in streamflow by 2050.

A recently released Colorado River Water Availability Study (Colorado Water Conservation Board Draft Report, 2010) focused on the State of Colorado's hydrometeorological contribution to the Colorado River system. The Study describes the tools available to model river hydrology, agricultural demands, water allocation, and decision support.

Finally, several papers in a recent special issue of the Proceedings of the National Academy of Sciences on Climate Change and Water in Southwestern North America (Sabo et al., 2010) focus on the climate and water supply in the Colorado River Basin. Cayan et al., 2010, provided an analysis of the current Colorado River drought and suggested that, while the current drought is exceptional in the observed record, future droughts in the Colorado River Basin may be more severe and longer in duration. Woodhouse et al., 2010, provided the 1,200-year perspective on southwestern drought, drew linkages of warming to paleo drought severity, and placed the drought in context with the medieval period worst-case drought. Seager and Vecchi, 2010, attributed the current and future southwest drying to a broader expansion of the Hadley cell that causes storms to track further north. It is important to note that the latter study (Seager and Vecchi, 2010) suggested decreases in winter (October-March) precipitation, while many other studies (including Cayan et al., 2010) suggested increases during this same period for much of the Colorado River Basin. It is not clear whether this discrepancy is due to the large domain (southwest North America, from southern Mexico to the Oregon-California border and from the Pacific Ocean to the High Plains) that is being averaged, or due to the lack of regional/local spatial resolution of the GCM-based information.

Across almost all research is the projection of continued and increased warming in the Basin and very likely increases in the severity of future droughts. However, the research suggests continued uncertainty in projections of the magnitude and direction of potential future changes in annual precipitation. Effective treatment of this uncertainty is important in making credible estimates of future water supply.

3.2.2 Data Sources

The Water Supply Assessment relied on a variety of peer-reviewed datasets collected by Reclamation, other recognized federal sources, and results obtained from the Variable Infiltration Capacity (VIC) hydrologic modeling performed by AMEC Earth & Environmental under contract with Reclamation (Reclamation, unpublished 2010). These data sources are listed in Appendix B3.

4.0 Historical Supply

An assessment of the historical climate and hydrology of the Basin is critical to facilitate a robust understanding of the projected changes associated with each of the four future water supply scenarios. For this reason, an assessment of the historical supply of the Basin is first presented. This presentation begins with a discussion of the methods used to perform the assessment, followed by the results for the four groups of water supply indicators: climate, hydrologic processes, climate teleconnections, and streamflow.

4.1 Methods

Historical daily temperature and precipitation for 1950 through 2005 (Maurer et al., 2002; Maurer et al., 2005) were processed into average temperature and total precipitation for each month and year of the period. Monthly, seasonal, and annual statistics were computed for each grid cell (1/8th degree, about 12 kilometers) of the gridded meteorological dataset for the 1971-2000 historical period to represent the historical climatology and compare to future projected climates. While the historical dataset represents one of the best long-term gridded meteorological datasets for North America, it should be recognized that this information is derived from individual NOAA Cooperative Observer station observations and gridded to the 1/8th degree using mapping algorithms that account for station elevation, or graphic effects, and other characteristics. Thus, the historical meteorological data represents a best estimate of distributed meteorological information over the broad region of the Colorado River Basin.

The 1971-2000 historical base period was selected as the most current 30-year climatological period as described by NOAA (2010) and is used as the basis for comparing to future climate projections[4]. The most current 30-year climatological period defined by NOAA (1971-2000) was used to establish a common historical period for comparison to projections of future climate. Data are typically averaged in 30-year periods as defined by the World Meteorological Organization. Climate change is the shift in the average weather, or trend, that a region experiences. Thus, climate change cannot be represented by single annual events or individual anomalies. That is, a single large flood event or particularly hot summer is not an indication of climate change, while a series of floods or warm years that statistically change the average precipitation or temperature over time may indicate climate change.

The historical climatological period allows for the averaging of individual year and multi-year variability over a longer period to capture the average conditions. A longer period could have been selected as the historical base period, but ensuring consistency with NOAA's period definition, and establishing a period consistent with tracking future changes (desire to estimate future changes for similar 30-year time slices), were considered important in this analysis. The seasons are defined as follows: Fall (October, November, and December); Winter (January, February, and March); Spring (April, May, and June); and Summer (July, August, and September).

Historical hydrologic parameter data were generated by the VIC model for the period 1950-2005. The VIC model (Liang et al., 1994; Liang et al., 1996; and Nijssen et al., 1997) is a spatially distributed macro-scale hydrologic model that solves the water balance at each model grid cell. The VIC model was populated with the historical temperature and precipitation data to simulate historical hydrologic parameters (Maurer et al,. 2002, 2005). Appendices B4 and B5 provide details on the VIC model and its application in the Study. Simulated hydrologic parameters include ET, runoff (surface runoff), baseflow (subsurface runoff), soil moisture (in each of three soil layers), and SWE. Representative statistics describing these parameters were again generated on monthly, seasonal, and annual bases. The statistical analysis was conducted on both grid cell and watershed bases. The results of the grid cell analysis produce the most informative map graphics and clearly show spatial

[4]A new 30-year historical base period (1981-2010) will be issued by NOAA toward the end of 2011.

variation at the greatest resolution possible, while the watershed basis provides an aggregate graphic of the variation across a natural flow station's watersheds.

Climate teleconnections were analyzed first by selecting indices that could have potential influence in streamflow changes for the Colorado River Basin. Published research (Redmond and Koch, 1991; Diaz and Kiladis, 1992; and McCabe et al., 2004, etc.) indicates that the strongest correlations with Colorado River Basin flows were observed with the ENSO and PDO indices. For ENSO, data were collected for both the ocean component (sea surface temperature anomalies) and the atmospheric component (sea level pressure anomalies). The two components are highly correlated, and combined, describe ENSO. The Southern Oscillation Index (SOI) was the primary dataset utilized in the Study to describe ENSO due to the longer period of data availability. Therefore, the quantitative teleconnections analysis was based on these SOI and the PDO indices. Only a qualitative discussion of the AMO is included in this report. For additional information pertaining to indices choice refer to Appendix B2.

Annual average values for the SOI were computed using different annual windows. The average SOI presented in the Study refers to the June to November period, a period that was identified as a strong indicator of ENSO events (Redmond and Koch, 1991). Once the SOI averages were computed, ENSO events were determined by years where the averaged SOI was below -1 (classified as an El Niño year) or above 1 (classified as a La Niña year). Annual averages of the PDO on a water year basis were calculated and compared with the same water year annual flows. A warm PDO was defined as a value greater than or equal to 0.0 and a cold PDO was a PDO value less than 0.0.

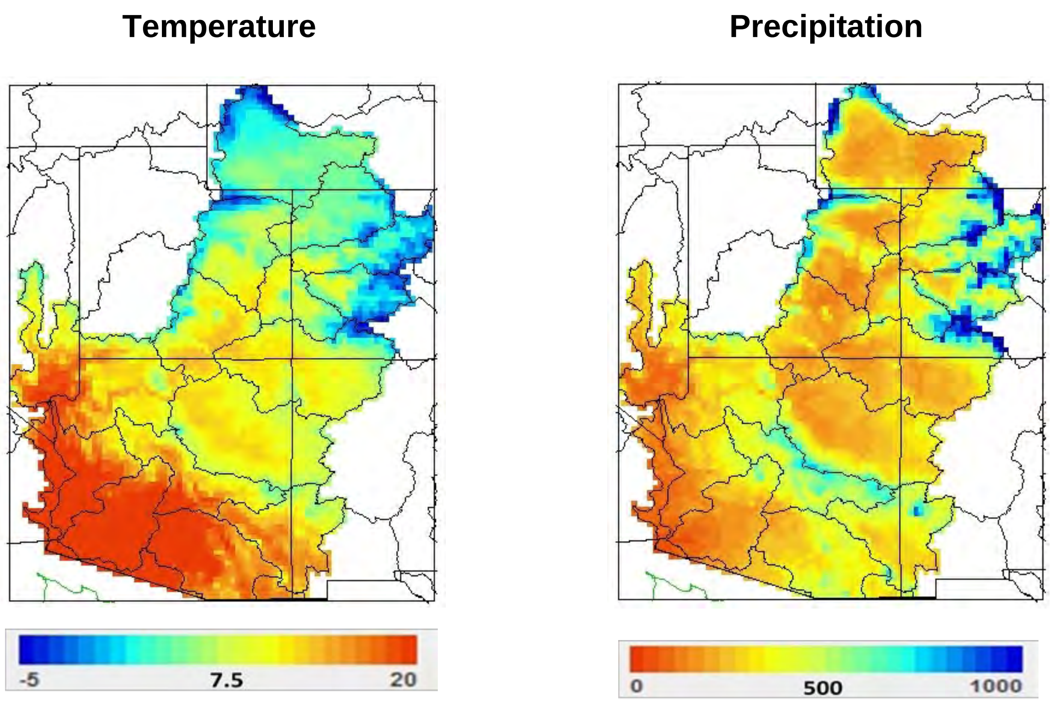
Two historical streamflow data sets, the observed rerecord spanning the period 1906-2007, and the paleo- reconstructed record spanning the period 762-2005 (Meko et al., 2007), were utilized in the Study to characterize historical streamflow patterns and variability. Period comparisons are made between the full extent of the data and a more recent period. For the observed dataset spanning 1906-2007, the second comparison period (1978-2007) was selected as the most recent 30-year period. For the paleo dataset spanning 762-2005, the second comparison period was selected as 1906-2005, such that direct comparisons could be made of the observed and paleo timeframes.

4.2 Results

4.2.1 Climate

The Colorado River Basin contains climate zones ranging from alpine to desert and is fundamentally influenced by climate variability from seasonal to millennial scales (National Research Council [NRC], 2007). The water supply of the Basin, as is typical in many western river systems, is strongly dependent on snowmelt from high elevation portions of the Upper Basin, with about 15 percent of the watershed area producing about 85 percent of the entire Basin's average annual runoff. Annual precipitation ranges from 84 millimeters (less than 4 inches) in southwestern Arizona to nearly 1,600 millimeters (63 inches) in the headwaters of Colorado, Utah, and Wyoming, as shown in Figure B-4. Average temperatures vary considerably by season, Basin location, and elevation, as also shown in Figure B-6. Warmest temperatures are seen in the southwestern Arizona summer and coolest in the headwaters during the winter.

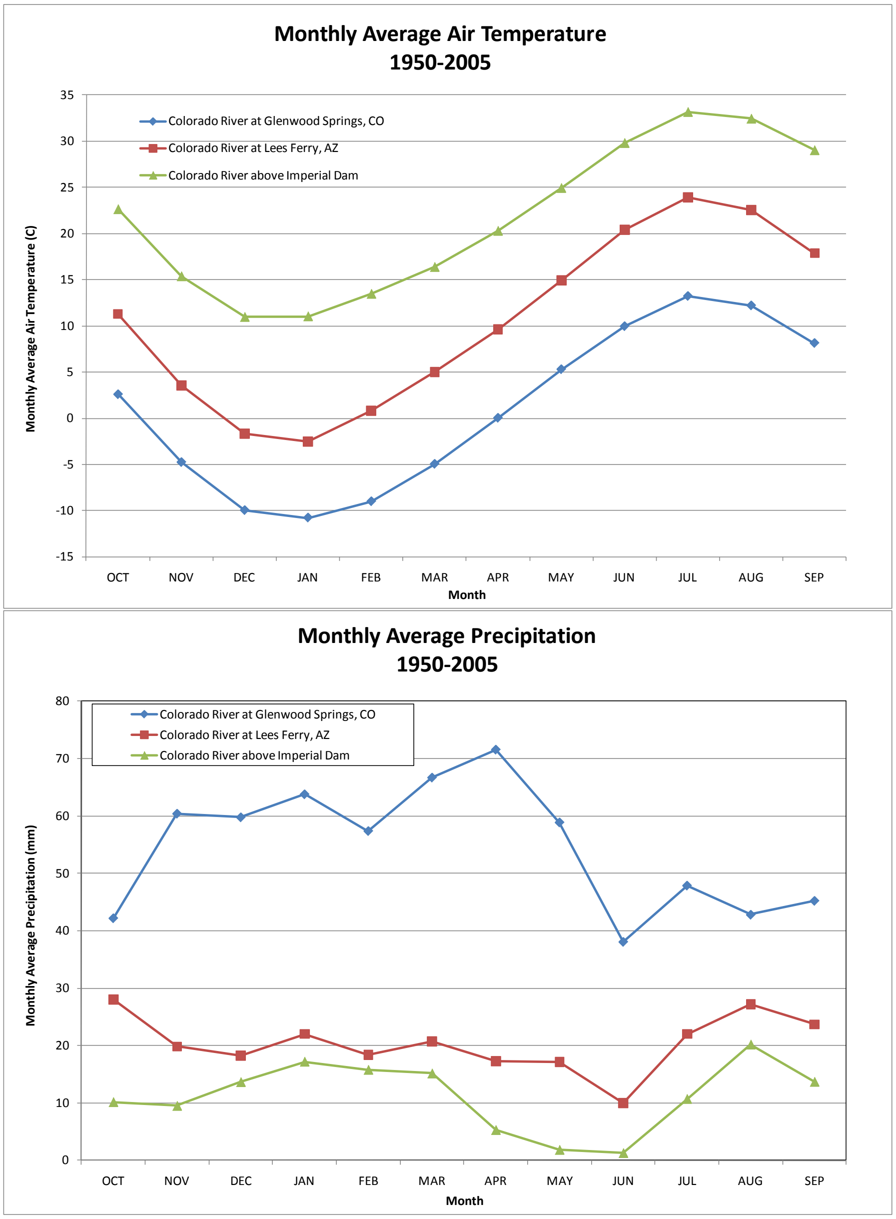
FIGURE B-4
Average Annual Temperature (deg C) and Average Annual Precipitation (millimeters) for the Period 1971 to 2000
(Derived from Maurer, 2002)



The climate of the Colorado River Basin exhibits important spatial and seasonal variability. To illustrate this variability, Figure B-5 shows monthly average temperature and precipitation as watershed averages for the areas immediately upstream of the Colorado River near Glenwood Springs (Colorado), Colorado River at Lees Ferry (Arizona), and Colorado River above Imperial Dam (Arizona/California). These three locations reflect a coarse transect of the Basin from the headwaters to Imperial Dam.

As illustrated in Figure B-5, the average temperature varies by more than 20°C seasonally at each of the three locations and similarly across the Basin within seasons. Cool winter temperatures at the higher elevation portions of the Upper Basin cause much of the precipitation to fall in the form of snow. At lower elevations, warmer conditions exist and liquid precipitation is the dominant form. For most regions, the majority of the precipitation occurs in the cool season (fall and winter). Warmer temperatures in the spring and summer induce snowmelt at the higher elevations while storms tend to be short and intense. The summer precipitation does not contribute a significant portion of the Basin annual total. However, in the southwest portions of the Basin (Arizona, California, and Nevada), summer precipitation is locally important. The North American monsoon season plays a significant role in bringing moisture from the sub-tropical Pacific and Gulf of California and causes intense summer storms in the southwestern desert. The monsoon influence extends into Upper Basin states as well and can contribute to significant summer precipitation in New Mexico, Utah, and Colorado.

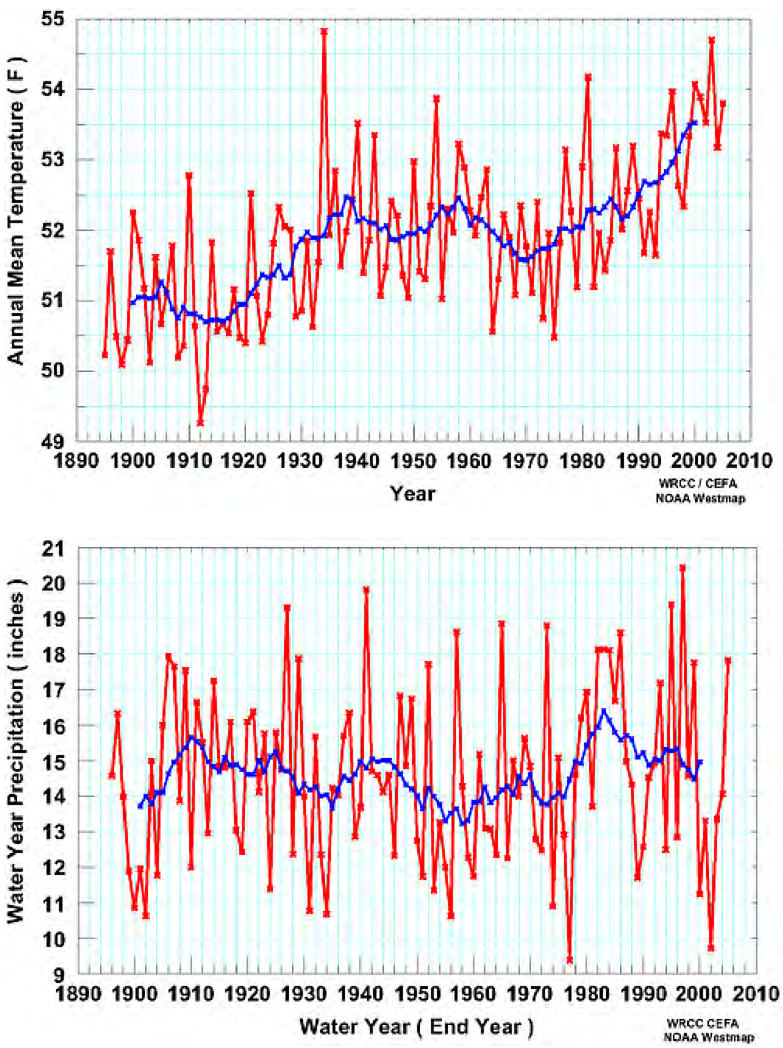
FIGURE B-5
Monthly Average Temperature and Precipitation for Three Representative Locations in the Colorado River Basin
Derived from daily gridded observed meteorology (Maurer et al., 2002, 2005) and averaged for the local watershed immediately upstream of the indicated point.



Trends in temperature and precipitation for the Colorado River Basin have been studied by Groisman et al., 2001; McCabe et al., 2002; Piechota et al., 2004; Hamlet et al., 2005; Pagano and Garen, 2005; Regonda et al., 2005; Andreasdis et al., 2006; Fassnacht, 2006; Mote, 2006; Christensen et al., 2007; and several others. Long-term trends are summarized in the 2007 NRC summary report on hydroclimatic variability in the Colorado River Basin (NRC, 2007). The long-term annual temperatures and precipitation amounts from 1895-2005 are shown in Figure B-6. A significant increase in temperature is apparent in this figure, although periods of cooling have occurred historically. Most important is the significant warming trend that has occurred since the 1970s. This warming trend is consistent with trends in both the Upper and Lower Basin and with observed North American and global trends.

Annual precipitation shows substantial variability and periods of dry and wet spells. Most notable in the precipitation record is the lack of a significant long-term annual trend, yet the annual variability appears to be increasing. Both the highest and lowest annual precipitation years appear in the most recent 30-year record.

FIGURE B-6
(Top) Annual Average Surface Air Temperature for the Colorado River Basin, 1895-2005; and (Bottom) Annual Water Year Average Precipitation for the Colorado River Basin above Lees Ferry
(Note: red lines show annual values; blue lines show the 11-year running mean. Source: NRC 2007 and Western Regional Climate Center.)

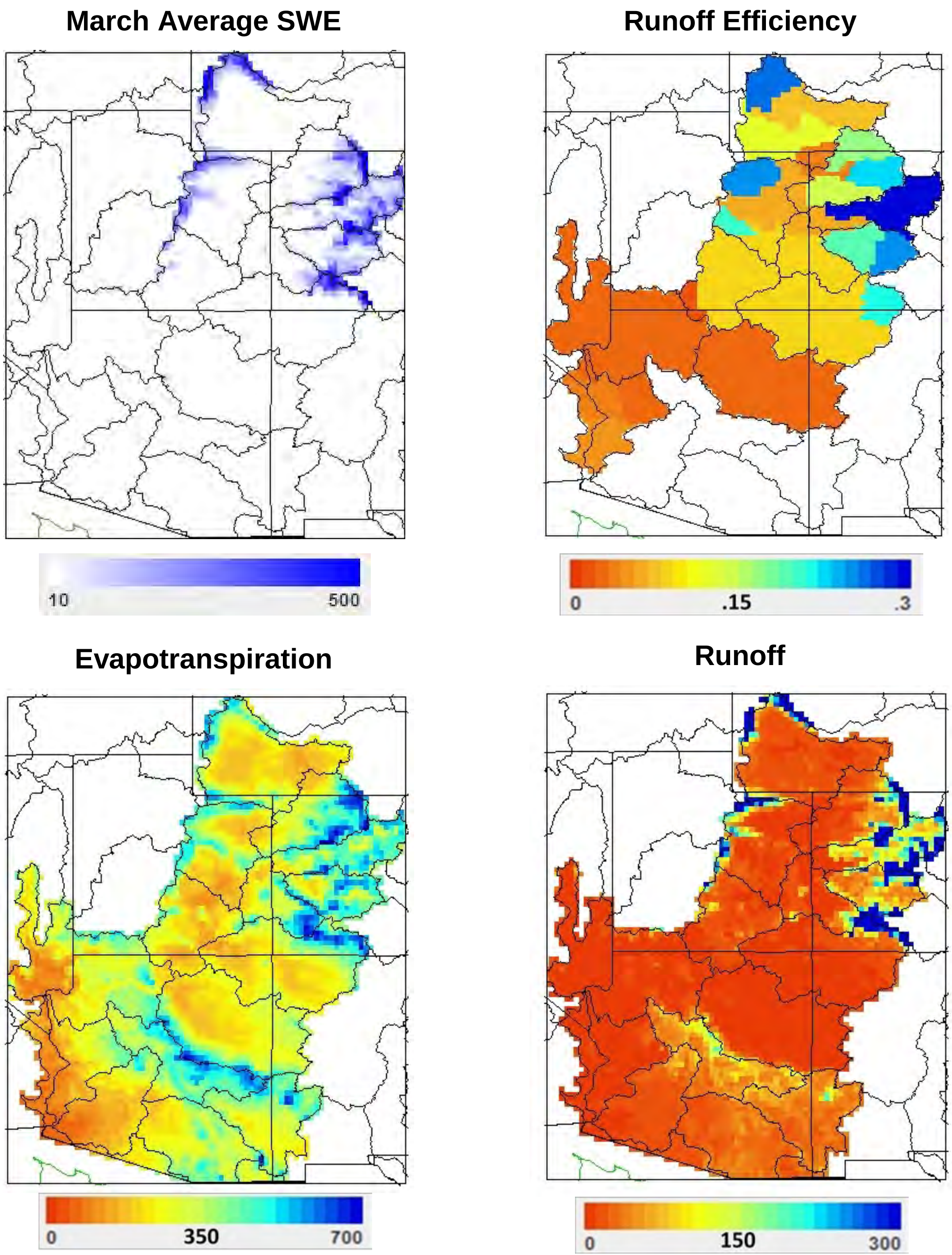


A 2008 publication by Miller and Piechota provides a summary of Colorado River Basin temperature, precipitation, and streamflow trends and also examines the possibility that a "step change" in these parameters occurred during the middle 1970s. The step-change time series data were divided into the first 24 years of data (1951 to 1974) and the later 31 years of data (1975 to 2005) for temperature and precipitation datasets. Miller and Piechota, 2008 found that increasing temperature trends and step changes were observed consistently throughout the year, often times at greater than a 95 percent confidence level. Temperature trends were most significant in the first quarter of the year, January through March. Precipitation trends and step changes were not as evident as those for temperature. An increasing precipitation trend was observed January through March, but not at all stations and not significant for other months.

4.2.2 Hydrologic Processes

The hydrologic processes that describe the interaction between climate and the watershed landscape are critically important in determining water availability and the manner in which the Basin response may change under future climate. The regions of greatest precipitation in the Colorado River Basin are those at high elevation in the headwaters of the Green, Colorado, and San Juan Rivers. Due to cold temperatures these areas accumulate substantial snowpack that is critical to the Basin supply. Figure B-7 provides an estimate of the average spatially-distributed March SWE for the period of 1971-2000 derived from a historical simulation of the VIC hydrology model. Correlations between observed and simulated SWE are 0.75 for the Rocky Mountain Region (Mote et al., 2008). Important in this figure is the relatively small portion of the watershed that offers significant seasonal water storage in the form of snowpack. While snow falls in other portions of the Basin, temperatures are generally not sufficiently cold to retain the snowpack for any great length of time. The remainder of this lower elevation portion of the watershed is predominantly rainfall dominated.

FIGURE B-7
Estimated Average Annual ET and Runoff (millimeters), Average March SWE (millimeters), and Annual Average Runoff Efficiency (fraction of precipitation converted into runoff) for 1971-2000 (derived from historical VIC simulations)

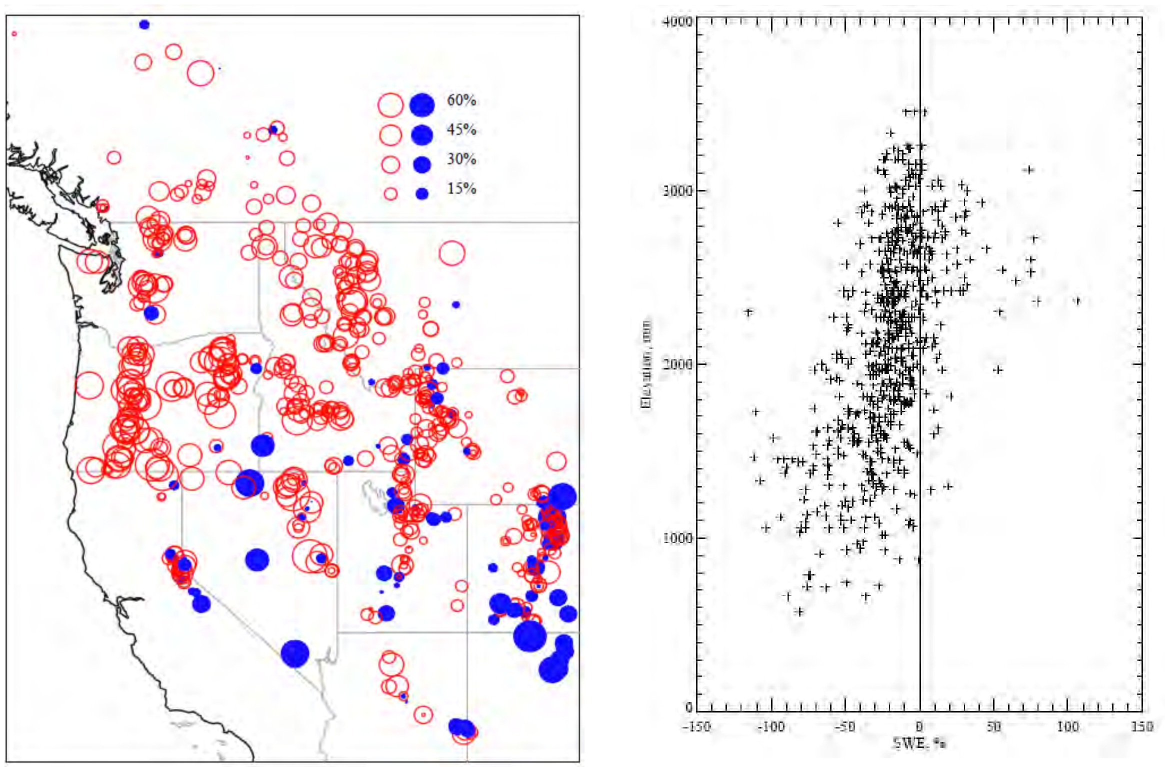


One way to synthesize many complex hydrologic processes at the watershed scale is to introduce the concept of runoff efficiency. Runoff efficiency is a measure of the effectiveness of a particular watershed in converting precipitation into runoff. Watersheds with very high runoff efficiencies dominate the overall contribution toward streamflow and have relatively lower losses. Watersheds with low runoff efficiencies have high losses and tend to be dominated by infiltration to soil moisture and consumptive use through ET. ET is the sum of evaporation from the land surface and plant transpiration. As can be seen in Figure B-7, the watersheds with the highest efficiencies are the headwaters of the Colorado, Green, and San Juan Rivers. These watersheds are able to convert about 20-30 percent of the precipitation into runoff and baseflow. However, even in the headwater regions there is considerable variability in runoff efficiencies with some values less than 10 percent. In the Lower Basin, average runoff efficiencies are all less than 10 percent and many watersheds have runoff efficiencies less than 5 percent. The runoff efficiency Basin-wide is about 12 percent.

ET is the dominant hydrologic flux on the annual scale, consuming more than 70 percent of the precipitation supply. As can be seen in Figure B-7, ET is highest in regions with greatest precipitation. This is not to say that the ET demand is highest in these regions, but rather that ET tends to be supply-limited in the Colorado River Basin. The ET demand (potential ET) is actually higher in the warmer climate of the Lower Basin, but water supply in the form of soil moisture is less and what is available is depleted earlier than in the Upper Basin watersheds.

Previously published research was relied on to assess observed snowpack trends in the Basin. Research by Mote, 2003, 2008; Clark et al., 2001; and Cayan, 2001 indicate a general decline in April 1 SWE for Pacific Northwest and northern Rocky Mountain locations, and increases in parts of the Great Basin and southern Rockies, as shown in Figure B-8.

FIGURE B-8
Left panel: Linear Trends in April 1 SWE at 594 Locations in the Western United States and Canada, 1950 to 2000 (Mote, et al., 2008) *(Negative trends are shown by open circles, positive by solid circles)*
Right panel: April 1 SWE Trends (1950-2000) Plotted against Altitude of Snow Course (Mote et al., 2008) (Units on Y-axis are incorrectly labeled as millimeters [mm] and should be meters).



Widespread decreases in springtime snowpack are observed with consistent results across the lower elevation northern latitudes of the West. The high elevation Rockies do not consistently produce decreasing trends for SWE. In order to assess the vertical characteristics of SWE, Mote plotted April 1 SWE trends (1950-2000) against altitude of snow course (Figure B-8). Losses of SWE tend to be largest at low elevations and strongly suggest a temperature-related effect.

Finally, Mote et al., 2008 used the VIC model to simulate SWE accumulation and depletion for western U.S. basins. From this analysis, it was clear that changes in SWE are not simply linear, but fluctuate on decadal time scales. SWE was estimated to have declined from 1915 to the 1930s, rebounded in the 1940s and 1950s, and despite a peak in the 1970s, declined since mid-century.

Additionally, recent research demonstrates dust-on-snow events have the ability to alter the timing and magnitude of runoff (Painter et al., 2010). Dust-on-snow events reduce snow albedo, or reflectivity, thereby increasing the solar radiation that reaches and warms the snow.

4.2.3 Climate Teleconnections

Research indicates a relationship between Pacific Ocean climate indices and Colorado River Basin streamflow. For the Study, relationships between the PDO and ENSO and natural flows in the Upper Basin were examined. Figure B-9 presents the annual PDO index and indicates when June to November SOI average values were below -1.0 or above 1.0.

FIGURE B-9
Plot of Water-Year Average PDO Values and ENSO Events Defined by SOI Averages for the Period June – November

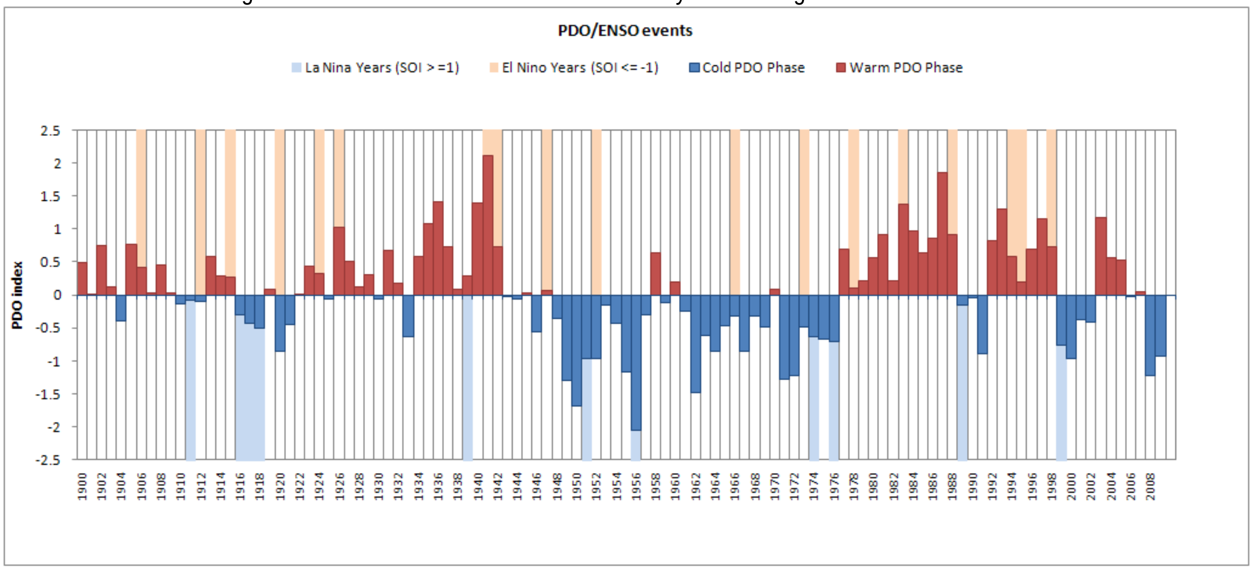
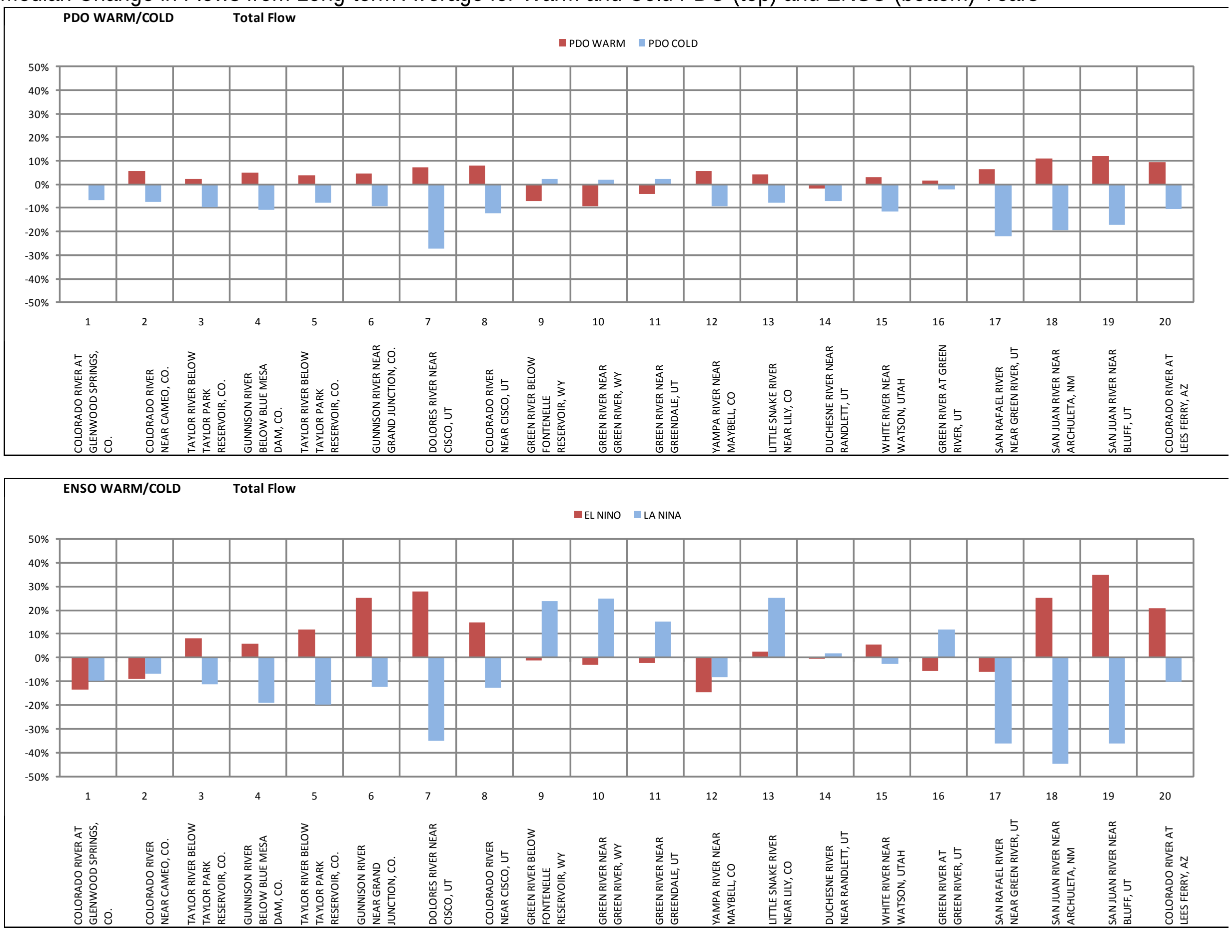


Figure B-10 illustrates water year departure from median streamflows in percent during warm and cold PDO and ENSO periods sampled from the period 1906-2007 for Upper Basin natural flow locations. The red bars indicate the streamflow departures for the warm phase of PDO (top) and ENSO (bottom), while the blue bars reflect the departures during the cool phases. Although significant streamflow variability exists from year to year, the majority of the flows are higher than normal during the warm PDO and ENSO (El Niño) phases. Conversely, the majority of the flows are lower than normal during the cool PDO and ENSO (La Niña) phases. It should be noted that the PDO and ENSO relationship is essentially inverted for the northern Colorado River Basin in Wyoming (Green River Basin). Further work will continue in this assessment to understand the relative and combined statistical significance of these climate teleconnections.

Overall, the natural inter-annual variability in streamflow tends to be more dominant than the relationships to either ENSO or PDO. ENSO has considerably more skill in the coastal watersheds of the Pacific, than over the Colorado River Basin. PDO, on the other hand, is a low frequency signal (multi-decadal scale) that limits the number of events that could be correlated. However, it is important to note that in our current year 2011, the climate is entering a strong combined cool phase of both ENSO and PDO. The alignment of both signals in the cool phase suggests a propensity for continued drying trends in the coming years.

FIGURE B-10
Median Change in Flows from Long-term Average for Warm and Cold PDO (top) and ENSO (bottom) Years

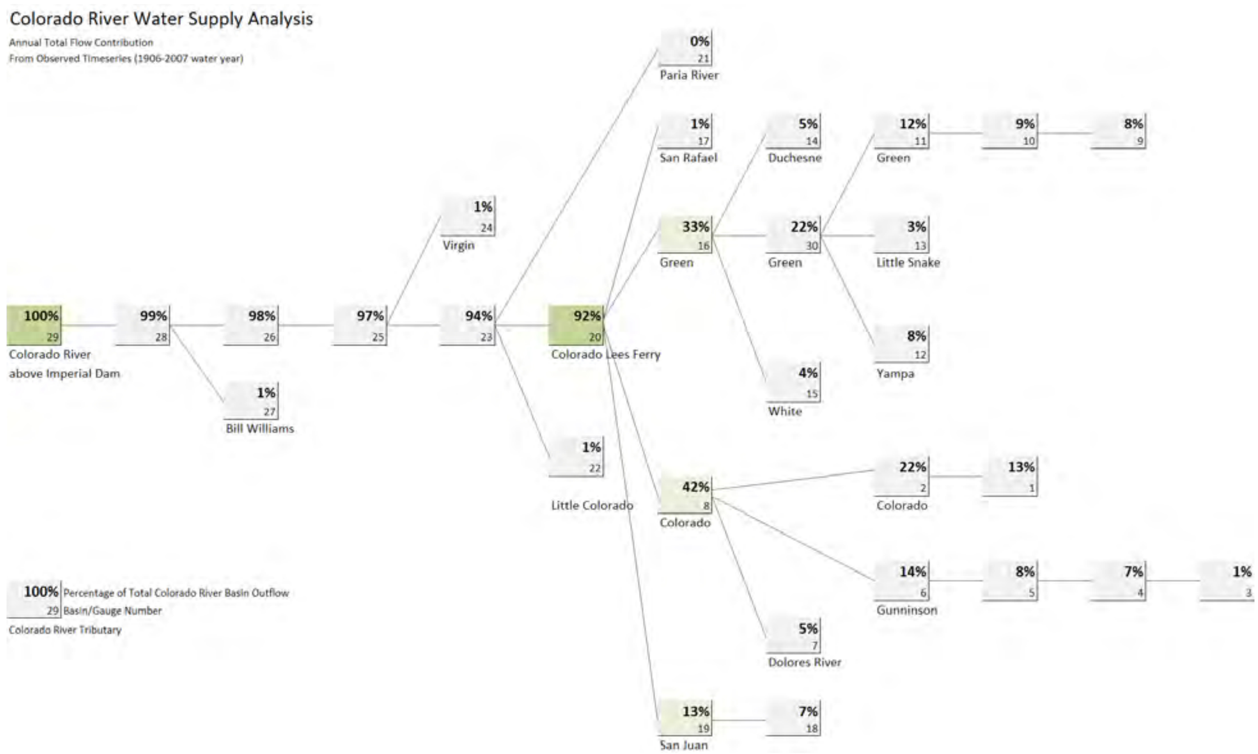


4.2.4 Streamflow

Observed

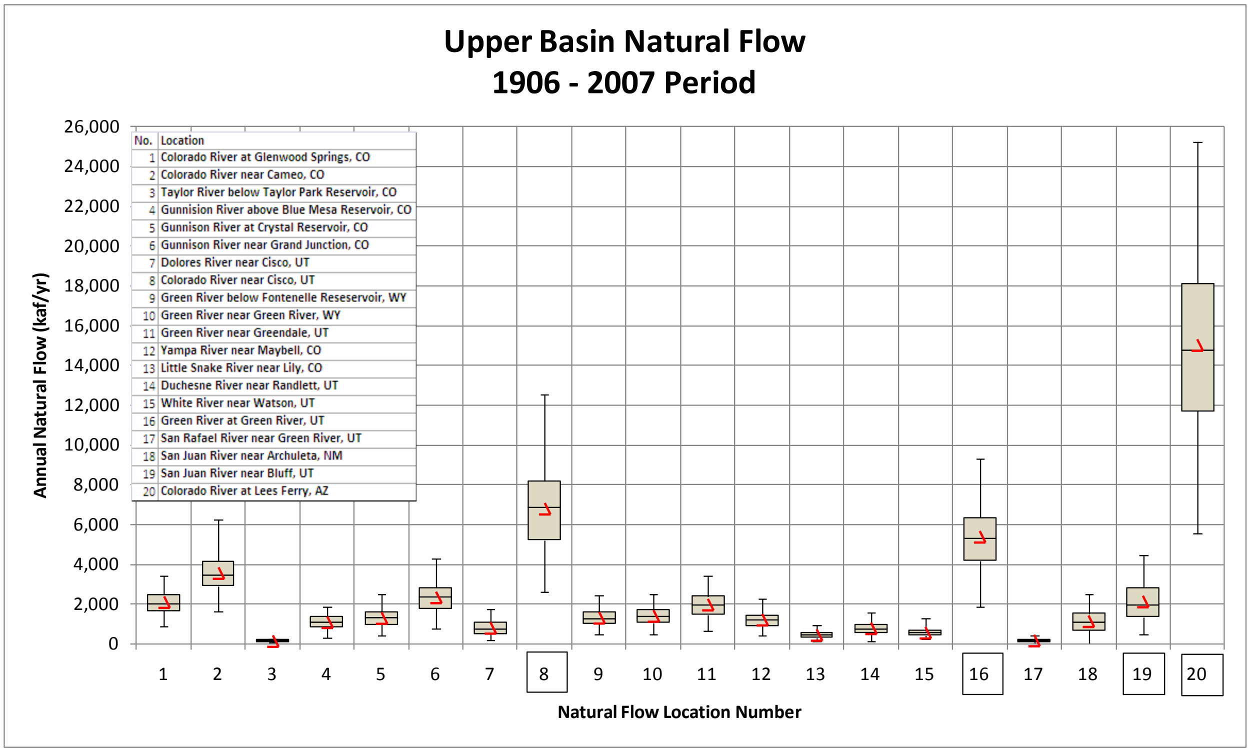
Analysis of streamflow records for the 29 natural flow locations indicated that about 92 percent of the total Colorado River natural flow is contributed by runoff upstream of Lees Ferry (Figure B-11). As shown graphically in Figure B-11, the Green River contributes about 33 percent of the total natural flow, the Colorado River at Cisco about 42 percent, and the San Juan River about 13 percent based on long-term annual natural flows from 1906-2007. Due to the importance of these rivers to the overall supply, they were selected as key locations for historical assessment. In addition, the Colorado River at Lees Ferry is used, as approximately 92 percent of the Basin flow has accumulated there.

FIGURE B-11
Colorado River Basin Average Annual Natural Flow Contribution (% of total) for each of the 29 Natural Flow Locations
Streamflow derived from the observed period (1906-2007). See Figure B-2 for names of locations.



The mean annual flows for 1906-2007 at each of the 20 Upper Basin natural flow locations are shown in Figure B-12. Also shown is the variability of annual flows as “box-whisker” ranges. The mean annual flow of the Colorado River at Lees Ferry (location 20) is approximately 15.0 million acre-feet (maf), but ranged from 5.6 maf (1977) to 25.2 maf (1984) over this period. The upper Colorado River at Cisco (location 8), Green River at Green River, Utah (location 16), and San Juan River at Bluff (location 19) have mean annual flows of 6.8 maf, 5.4 maf, and 2.1 maf, respectively.

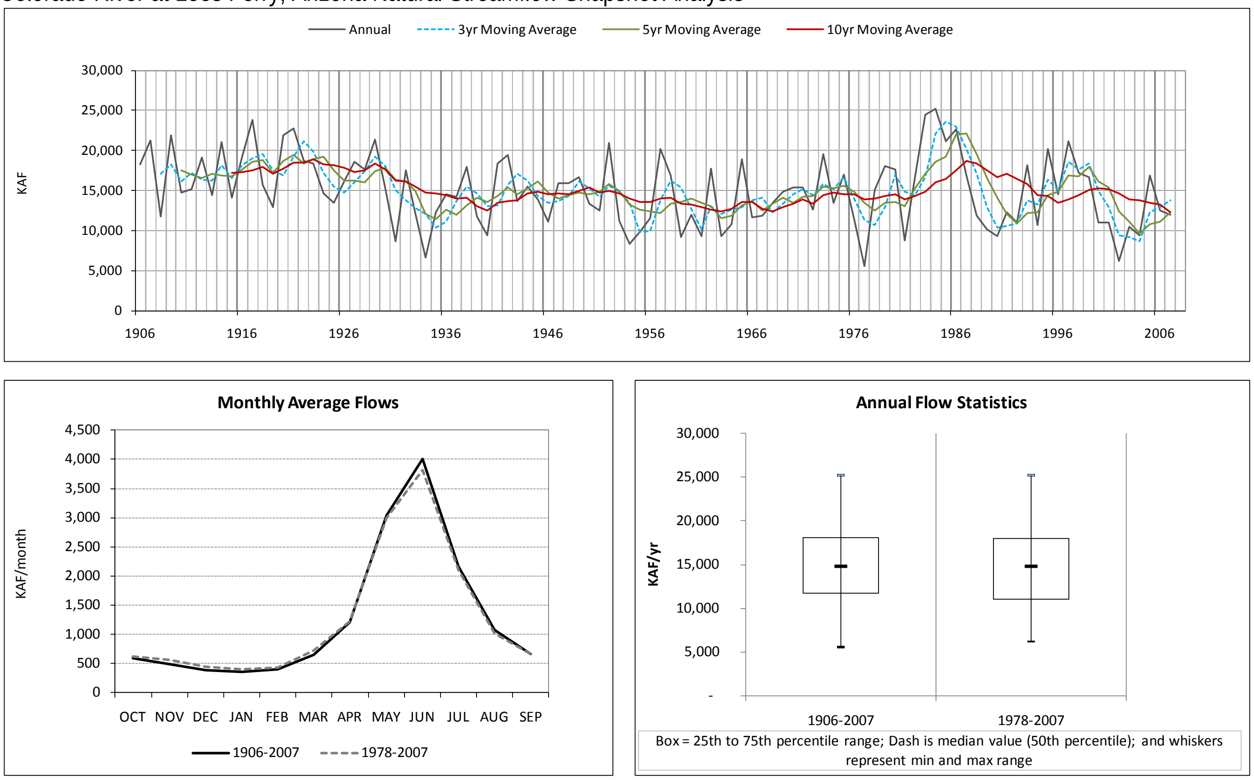
FIGURE B-12
Upper Basin Average Annual Total Natural Flows
(Box represents the 25th, 50th, and 75th percentile, whiskers represent the maximum [max] and minimum [min], and triangle represents the mean flow)
Streamflow derived from the observed period (1906-2007)



Streamflow analysis summaries ("snapshots") were prepared for all 29 natural flow locations to evaluate the trends and variability of flows. Four snapshot summaries are presented in this report for the following key locations: Colorado River near Cisco (Location 8); Green River at Green River, Utah (Location 16); San Juan River near Bluff (Location 19); and Colorado River at Lees Ferry (Location 20). Complete streamflow analysis figures for each of the major contributing flow locations are included in Appendix B6. This complete summary includes a table reporting specific monthly streamflow averages, annual averages including minimum and maximum values with the years they occurred, and a more-detailed analysis of deficit/surplus periods.

The snapshot results were developed from the natural flows dataset using data for water years 1906-2007 (Figures B-13 to B-16). The top plot in each figure shows the annual flow volumes and the moving averages for 3, 5, and 10 years. This plot provides a visual assessment of streamflow variability, minimum and maximum flows, and long-term trends. For most selected locations, more variability and extreme events are observed after 1976. Generally lower flows are observed from the mid 1930s to mid 1960s and a slightly downward trend in flows is observed in all locations for this time period. As an example, the Lees Ferry plot (Figure B-13) shows a period of generally below average streamflow and a period of moderate variability for the period 1930-1976. Beginning in 1977, streamflow amplitude and variability increased with a decrease in streamflows beginning in approximately 1986.

FIGURE B-13
Colorado River at Lees Ferry, Arizona Natural Streamflow Snapshot Analysis



The bottom left plot shows a two-period comparison of monthly average streamflow. The first period spans 1906-2007, while the second period captures the most recent 30-year period, 1978-2007. For the period 1978-2007, all selected locations exhibit a reduction in late spring streamflows and a slight increase in winter streamflows when compared to the long-term (1906-2007) averages. The annual median at all selected locations, with the exception of the San Juan near Bluff, is visibly higher during the 1978-2007 period. This is because there were two significant high flow periods (the early-mid 1980s and the late 1990s) that occurred at these locations during this period. Although the most recent comparison period is shorter than the long-term data record, streamflow variability was essentially unchanged. The major cause of the similar annual variability between the two periods is that the maximums and minimums for the 1-, 3-, and 5-year averages over the entire 102-year period of record have mostly all occurred in the most recent 30-year period and are thus represented in both periods (most recent period is also included in the long-term period).This finding is consistent with precipitation trends that show increased variability in the recent period. For the San Juan near Bluff, Utah (Figure B-16) it appears, based on the inter-quartile (25^{th} to 75^{th} percentile) range, that streamflow variability during the 1978-2007 period is relatively unchanged. The two highest flows at this location occurred in 1941 and 1973.

FIGURE B-14
Green River at Green River, Utah Natural Streamflow Snapshot Analysis

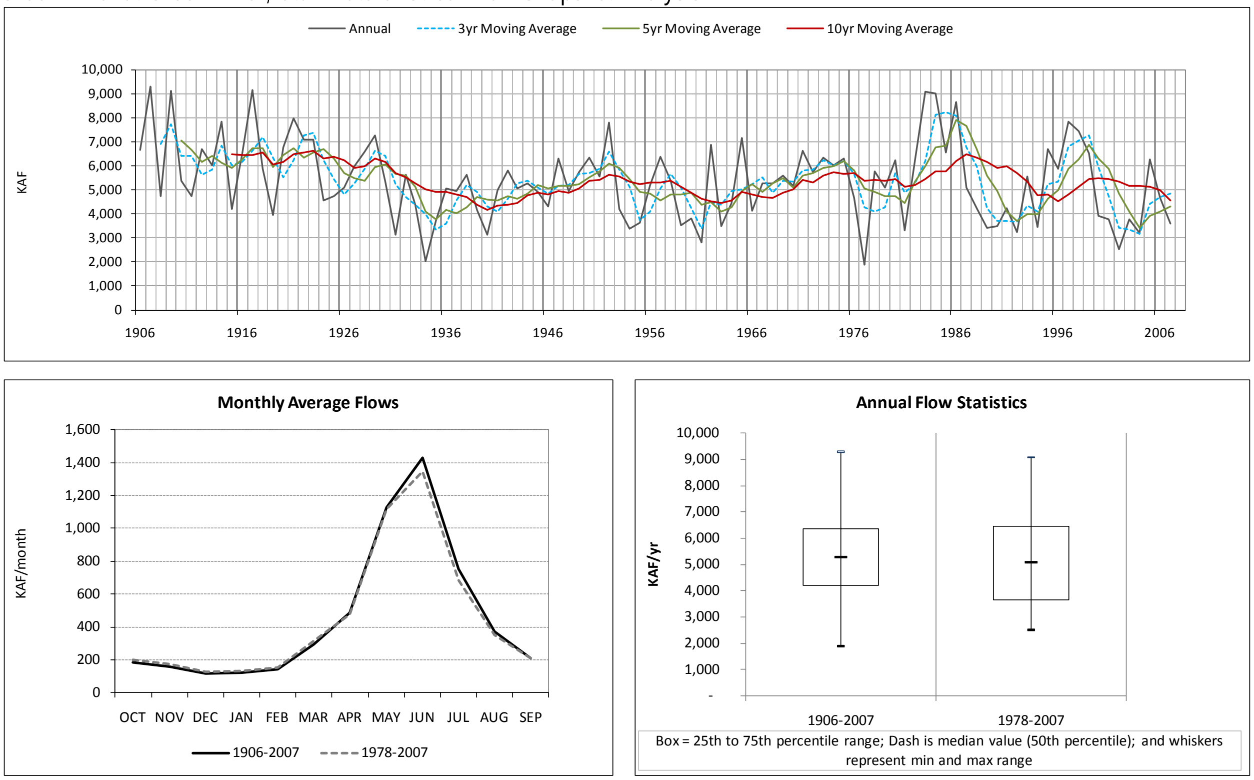


FIGURE B-15
Colorado River near Cisco, Utah Natural Streamflow Snapshot Analysis

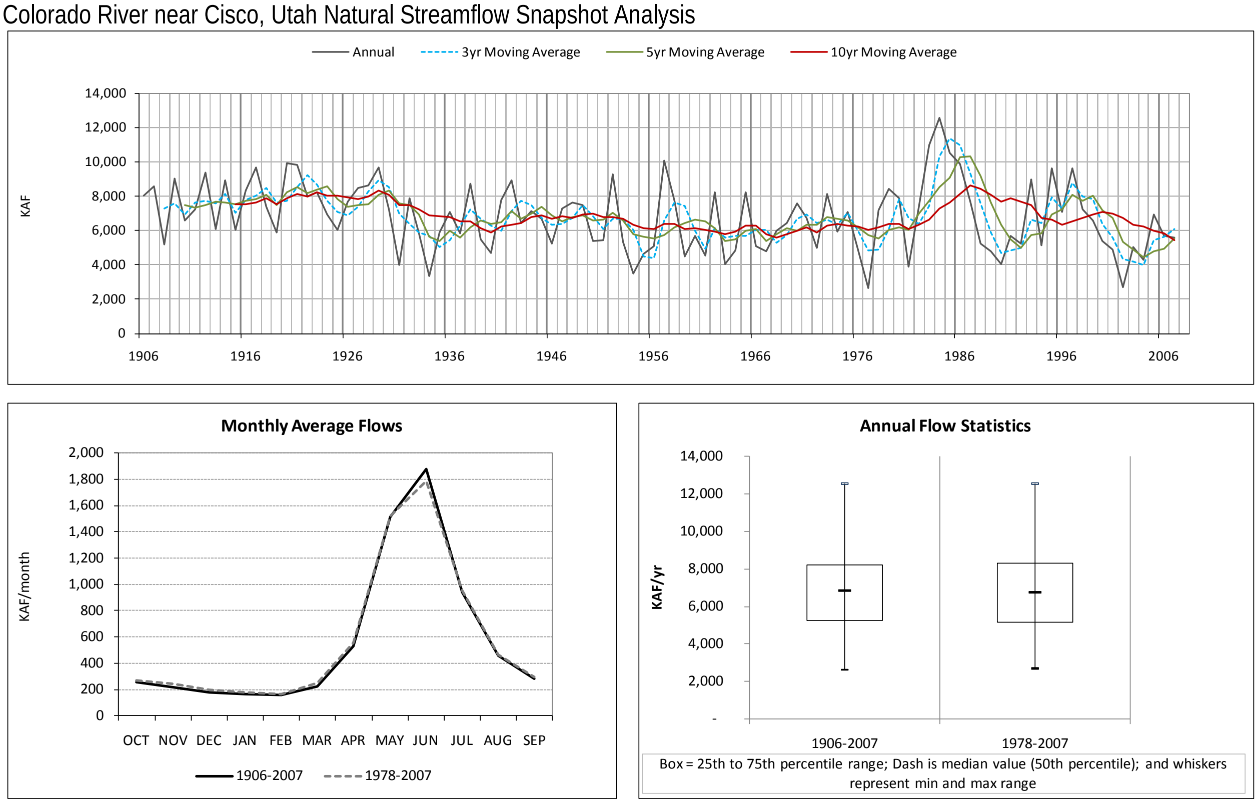
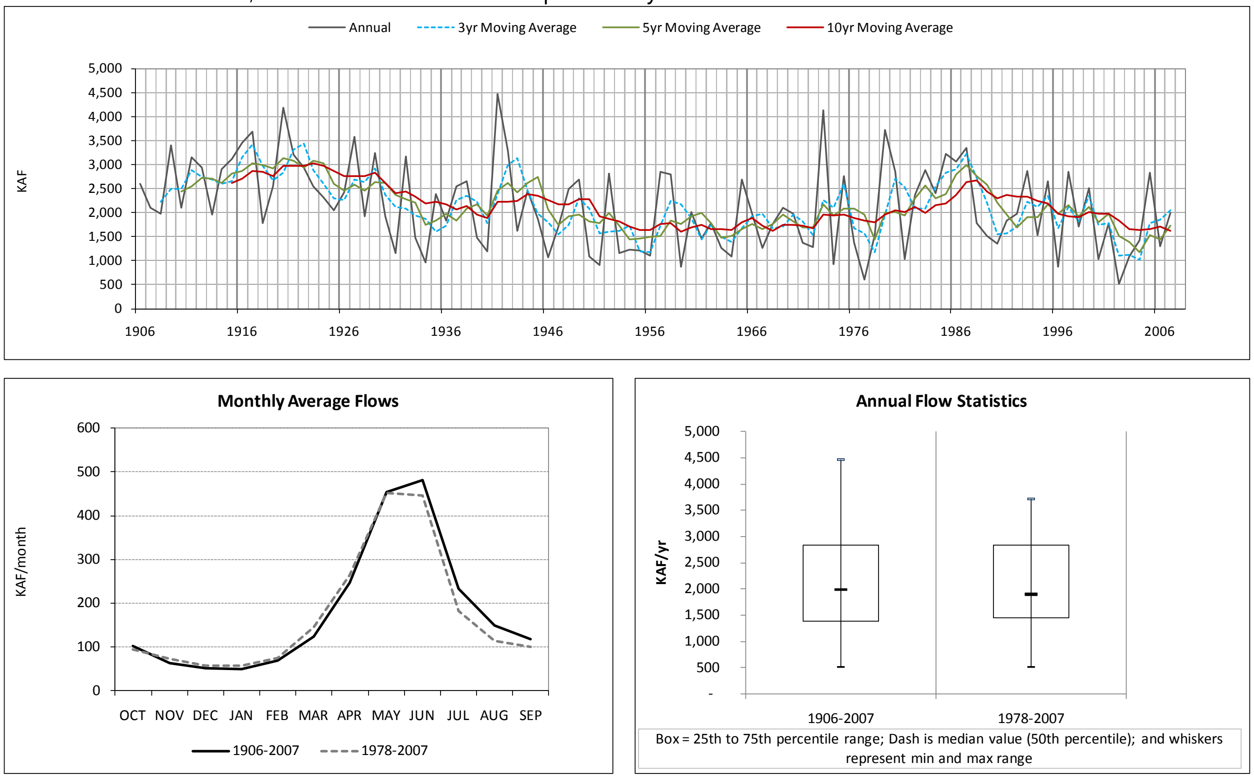


FIGURE B-16
San Juan River near Bluff, Utah Natural Streamflow Snapshot Analysis



As with temperature and precipitation, Miller and Piechota, 2008 also evaluated streamflow trends and explored the significance of a step change in streamflow, which occurred during the mid 1970s. The step change time series data were divided into the first 69 years of data (1906- 1974) and the latter 31 years of data (1975-2005). Increasing streamflow trends in January through March and decreasing streamflow trends during peak runoff months (April through July) were seen in the authors' study. The authors also noted that decreasing streamflow trends were apparent at the 99 percent confidence level throughout the Colorado River Basin during the traditional peak flow months, despite the high variability of streamflow rates that have historically occurred in the Basin (e.g., Pagano and Garen, 2005; Woodhouse and Lukas, 2006). Since streamflow trends are more apparent than precipitation trends, the authors speculate that it is possible that the state (i.e., rain or snow) and interaction of precipitation (e.g., evaporation and seepage losses) are changing. Based on these studies, a general warming in the Basin is shifting winter precipitation to a higher rain-snow ratio when compared to historical data. These changes can correspond to earlier peak streamflows in the spring.

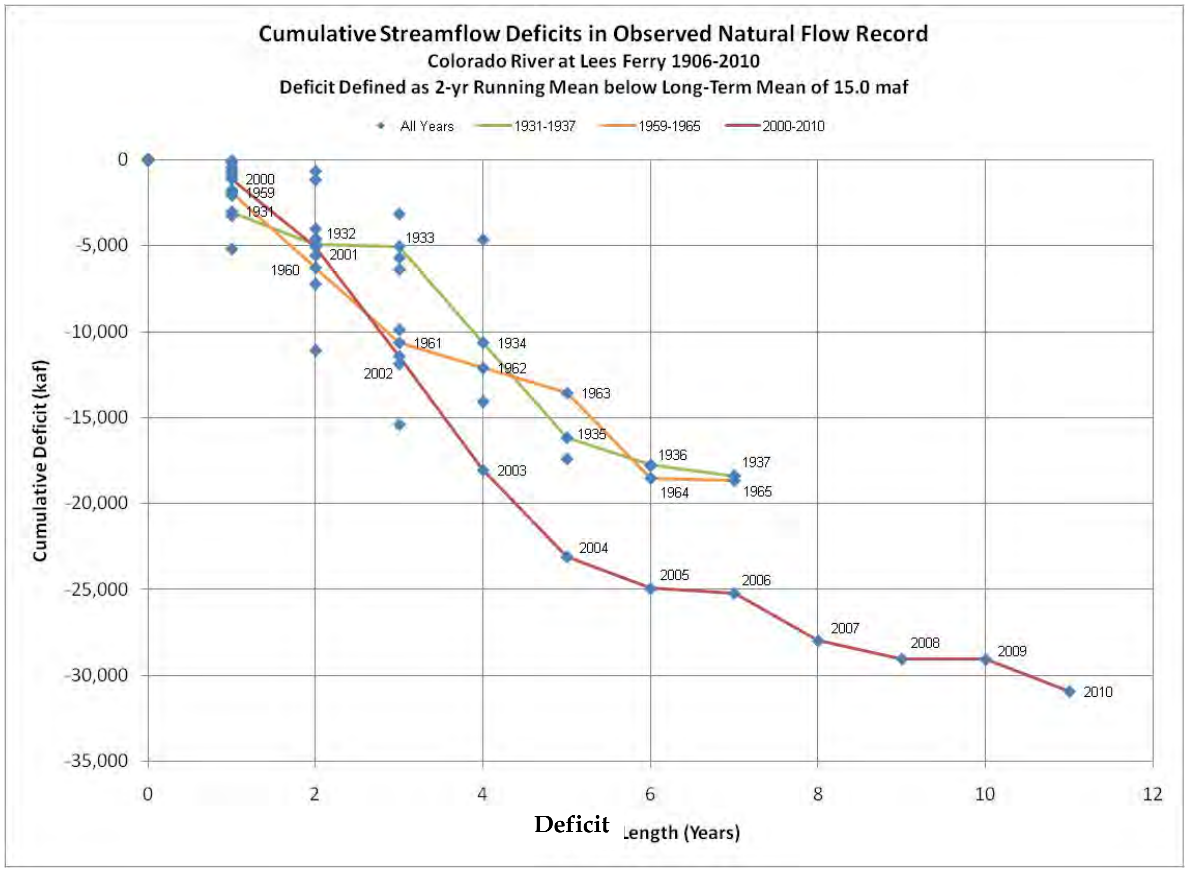
The inter-annual variability of climate and hydrology within the Basin produces frequent periods when the mean flow during that period is below the long-term mean. These occurrences are referred to as periods of streamflow deficit or deficits for the purpose of this report. As part of the analysis conducted for this report, different averaging periods for determining and measuring deficits were considered. The use of a 1-year averaging period was discarded because it implied that any one year above 15 maf of natural flow at Lees Ferry would break a multi-year deficit. The use of a 2-year averaging period implies that it may take two consecutive, above-normal years (or one extremely wet year) to end a deficit.

The definition used in the remainder of the report is the following: “a deficit occurs whenever the 2-year average flow falls below 15 maf, the long-term mean annual flow of 1906-2007.”

Applying this definition, Figure B-17 presents the severity of deficits in the observed record. For each year of 1906-2010[5], the 2-year running average annual flow was calculated. The difference between the 2-year running average flow and the long-term mean annual flow was computed. If the difference was negative, then this was labeled “deficit” and the volumes were accumulated until the difference was once again positive. The deficit length and cumulative amount were recorded for each year. Three significant deficit spells that occurred in the observed period beginning in 1931 (7-year deficit), 1959 (7-year deficit), and 2000 (11-year deficit) are shown on the figure in green, orange and red, respectively. As can be seen from the figure, the current deficit that began in 2000 is still in existence and has accumulated an 11-year deficit of more than 30 maf. This current deficit is more severe than any other deficit in the observed period.

[5]The natural flow at Lees Ferry extended to 2010, based on provisional natural flow estimates (Prairie 2011 unpublished), is used here to better reflect the current state of streamflow deficit.

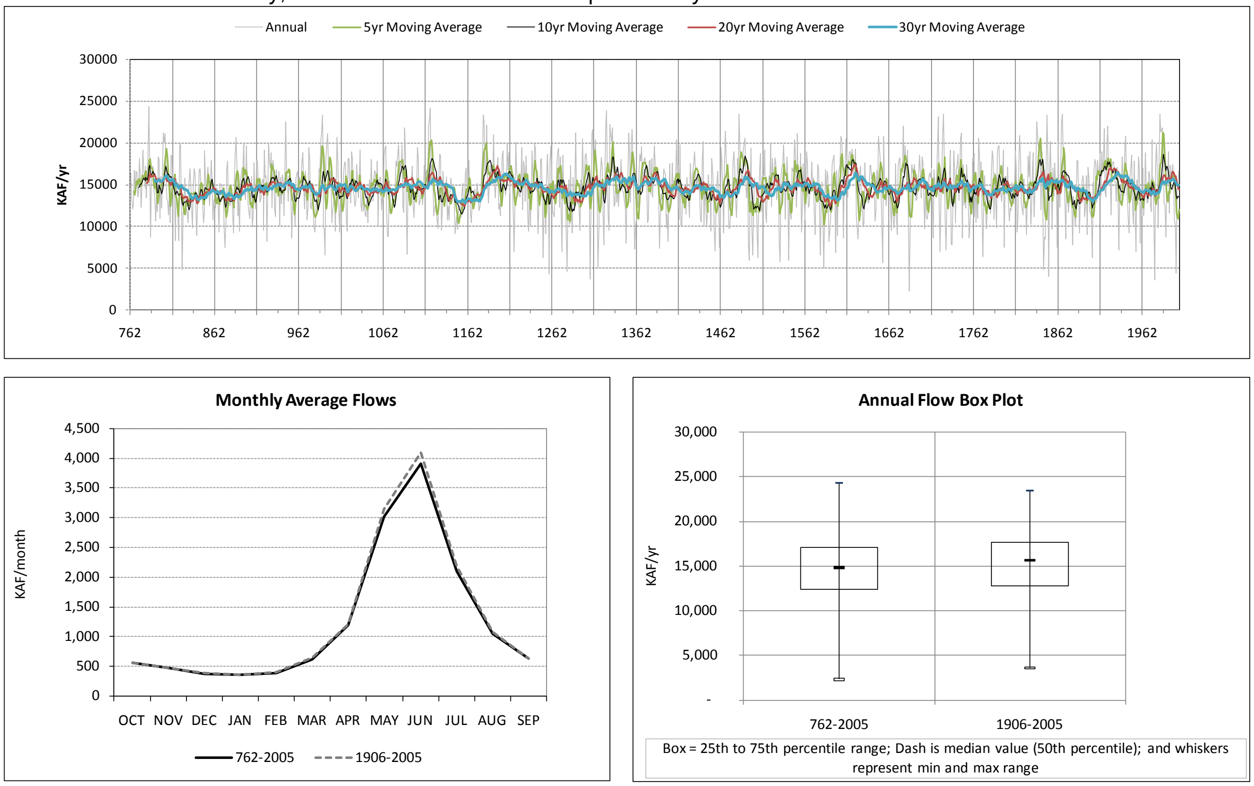
FIGURE B-17
Cumulative Streamflow Deficits (defined as 2-year running mean below 15 maf) for the Colorado River at Lees Ferry
(Note: 2008-2010 natural flows are provisional)



4.3 Paleo Reconstructions of Streamflow

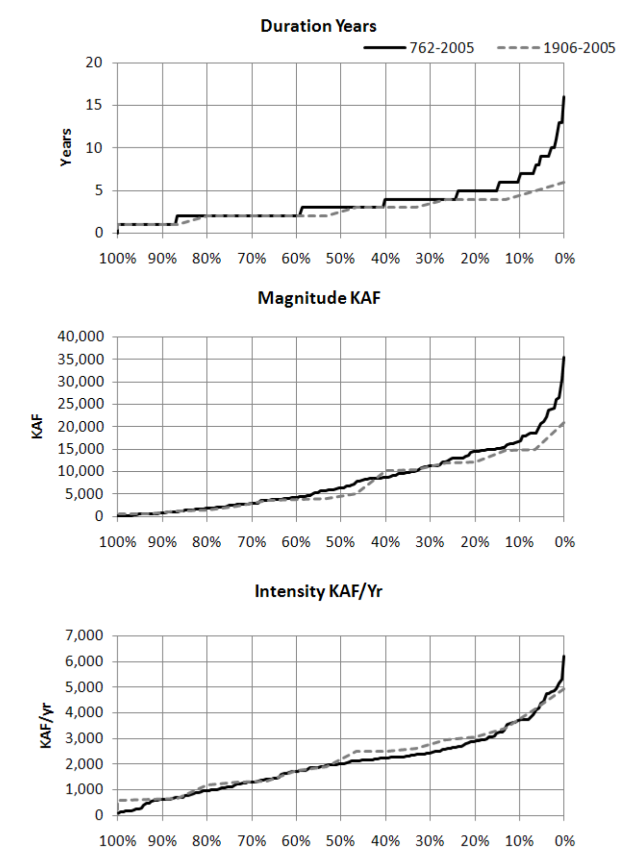
A summary of the snapshot results for Colorado River at Lees Ferry from the paleo-reconstructed 762-2005 period is shown in Figure B-18. The top plot shows the annual flow volumes and the moving averages for 3, 5, 10, 20, and 30 years for the period of record. This plot provides a visual assessment of streamflow variability, minimum and maximum flows, and long-term trends. Period comparisons between long-term paleo- reconstructions (762-2005) and a segment of the observed record (1906-2005) are shown. The annual flow box plot shows the minimum, 75th, 50th, and 25th percentiles, and maximum annual streamflows for the two analysis periods. The minimum, 25th percentile, median, and 75th percentile are all slightly less in the paleo- reconstructed record, indicating that the paleo- reconstructed streamflows are lower than the observed record. Variability is increased in the paleo-reconstructed record as illustrated by the broader inter-quartile range and minimum/maximum values.

FIGURE B-18
Colorado River at Lees Ferry, Arizona Paleo Streamflow Snapshot Analysis



Streamflow deficits using the same methods as described in the previous section were similarly computed for the 762-2005 period and the 1906-2005 period and statistics are presented in three exceedance plots (duration, magnitude, and intensity) in Figure B-19. The 762-2005 period contains deficits that are longer in duration (16 years) and have larger deficits (as much as 35 maf) than the 1906-2005 period. Thus, the sequences of wet-dry states from the much longer paleo record suggest that deficits of greater severity than the current deficit are possible. Interestingly, the deficit intensity (defined as the cumulative deficit divided by the duration of the deficit, which can give an indication of the annual severity of deficits) is similar between the two periods, suggesting that the paleo record produces longer deficits, but that they may not be any more intense on an annual basis than the observed record.

FIGURE B-19
Comparison of Drought Characteristics between a Segment of the Observed Period (1906-2005) and the Paleo Period (762-2005)



In summary, the trends over the observed period and over the recent climatological regime suggest declining streamflows, increases in variability, and seasonal shifts in streamflow that are likely linked to warming. The paleo reconstructions indicates a slightly lower mean than the observed record. These paleo reconstructions suggest the annual and inter-annual flows have been more variable in terms of both wet and dry sequences, as compared with the observed record period. Deficits of longer duration and greater magnitude can be expected based on the paleo record, although the paleo record shows that past deficits were not significantly more intense than the observed record.

5.0 Future Supply under the Observed Resampled Scenario

5.1 Methods

Used by Reclamation in several past planning studies, the Observed Resampled[6] scenario is quantified by applying the Indexed Sequential Method (ISM) (Ouarda et al., 1997) to the

[6]The Direct Natural Flow, Direct Paleo, and Nonparametric Paleo Conditioning scenarios analyzed in Appendix N of the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead Final EIS are synonymous with the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios analyzed in this report, respectively.

1906-2007 observed natural flow record to generate 102 sequences, each 50 years in length. ISM is a stochastic resampling method that is used to create a number of different future hydrologic sequences (or realizations). The length of the hydrologic sequence is determined by the simulation horizon (2011-2060, or 50 years in the Study) and the number of sequences is determined by the length of the record that is being resampled (1906-2007, or 102 years in this scenario). The ISM cycles through the observed record generating 102 hydrologic sequences, based on the assumption that the record “wraps around” at the end (i.e., 2007, 1906, and 1907).

Strengths of this method are that it is based on the best available measured data, provides the basis for a quantification of the uncertainty and an assessment of risk with respect to future inflows, and is widely accepted by stakeholders on the Colorado River. The major drawback of this approach is future scenarios are limited to the magnitudes and sequencing that occurred in the observed record, with the exception of new sequences generated as a result of the wrap. Therefore, a wider range of plausible future streamflows (including flow magnitudes and wet and dry sequences not seen in the observed record) are not possible in the Observed Resampled scenario.

5.2 Results

The results for the Observed Resampled scenario are presented as summary figures for annual and monthly flows at Colorado River at Lees Ferry in Figures B-20 through B-23. Since each supply scenario includes multiple hydrologic sequences, there is a range associated with the flow statistics. Figure B-20 displays all of the individual 102 sequences in the Observed Resampled scenario. The sequence bolded in Figure B-21 also appears in Figure B-21, which is a statistical summary of the 102 sequences. Figure B-21 depicts the annual range of natural flows when applying the ISM technique, while Figure B-22 provides the annual statistics.

Annual natural flows are generally in the range of 5-25 maf, with a mean of approximately 15 maf. The standard deviation is almost one-third of the mean annual flow, providing a representation of the inter-annual variability of this flow record. Skew is a measure of the shape of the annual flow distribution. A skew of zero implies a perfectly “normal” distribution in which wetter years and magnitudes are evenly balanced with drier years. The skew and backward lag correlation indicate that the flows are slightly biased to the lower side of the distribution (more dry years than wet years) and that year-to-year correlation of flows is relatively high.

FIGURE B-20
Colorado River at Lees Ferry Natural Flow for 102 Sequences for the Observed Resampled Scenario

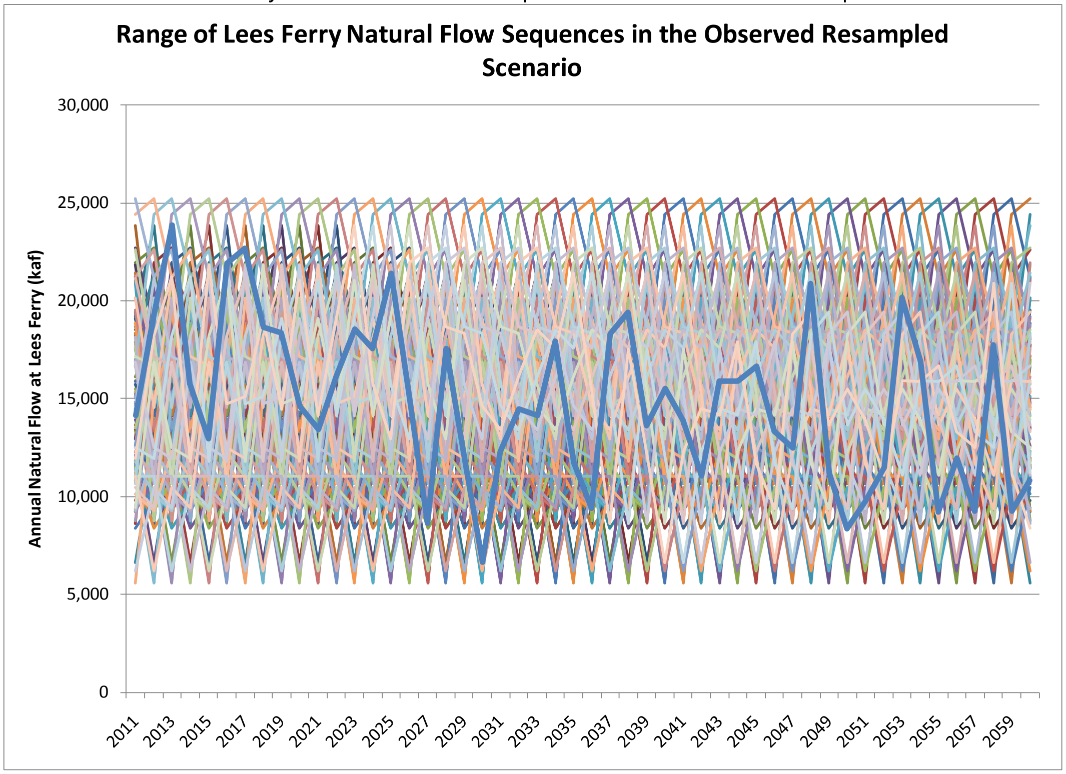


FIGURE B-21
Simulated Annual Colorado River at Lees Ferry Natural Flow Statistics for 102 Realizations, 2011-2060
Figure shows the median (line), 25th – 75th percentile band (dark shading), 10th – 90th percentile band (light shading), max/min (whiskers), and a representative trace (line).

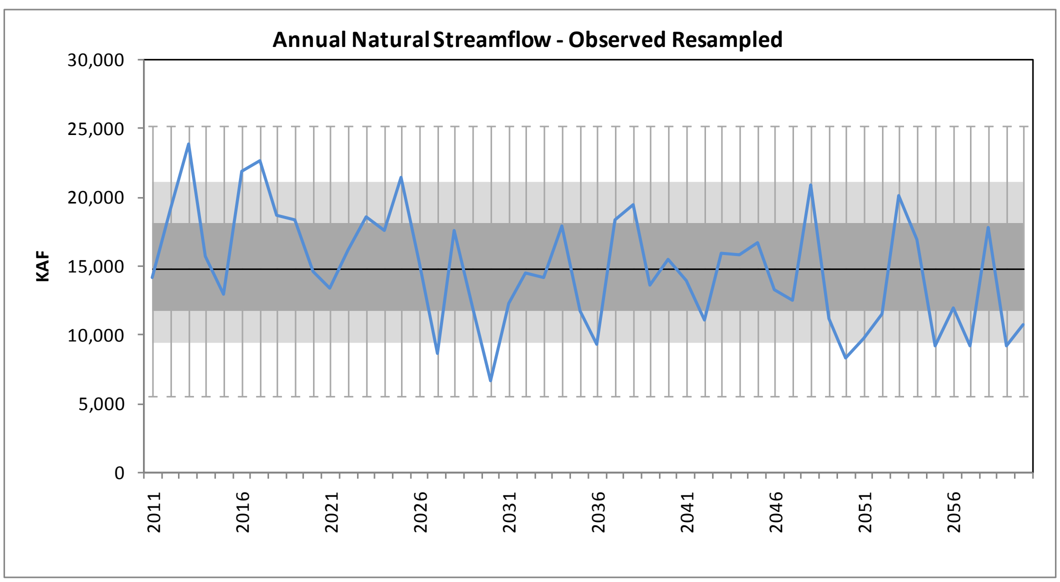
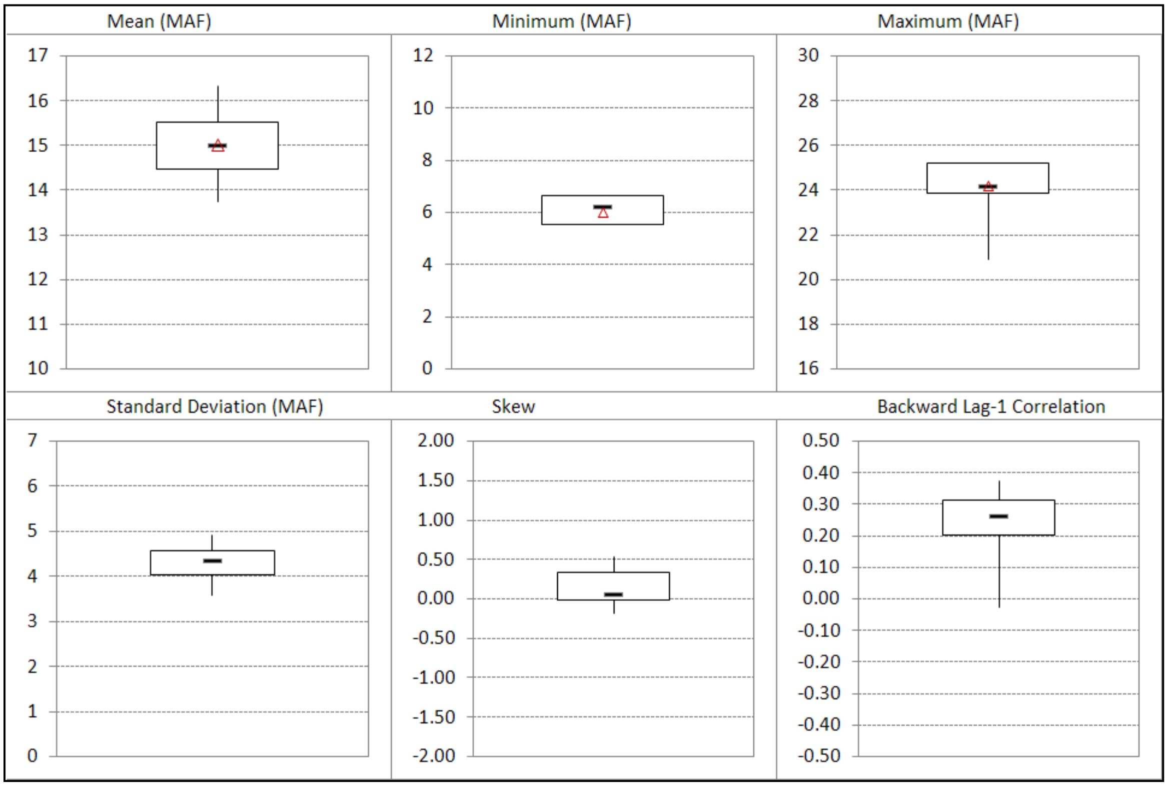
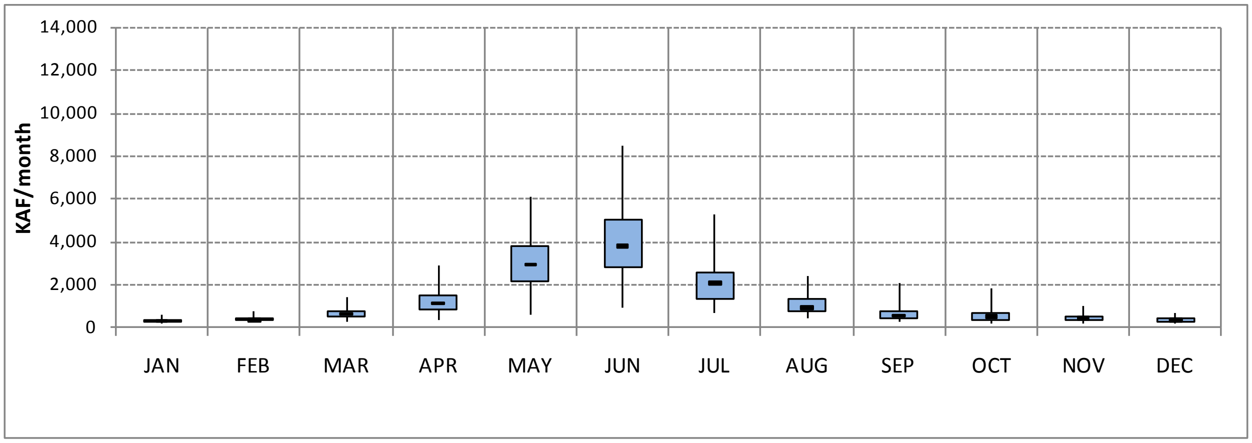


FIGURE B-22
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for the Observed Resampled Scenario
Figure shows the median (dash), 25th – 75th percentile band (box), and max/min (whiskers).



River flow peaks in late spring due to delayed snowmelt from the higher elevation upstream watersheds with May, June, and July exhibiting the highest flows (Figure B-23). June flows are both the highest and most extreme, with mean monthly flows averaging about 4 maf/month and ranging from about 1-9 maf/month. Late summer and fall flows are considerably lower and exhibit significantly less variability. The Paleo Resampled and Paleo Conditioned scenarios exhibit nearly the same monthly statistics; however, the Downscaled GCM Projected scenario indicates a shifting of the highest flow month from June to May, with considerably more variability (see Figure B-46).

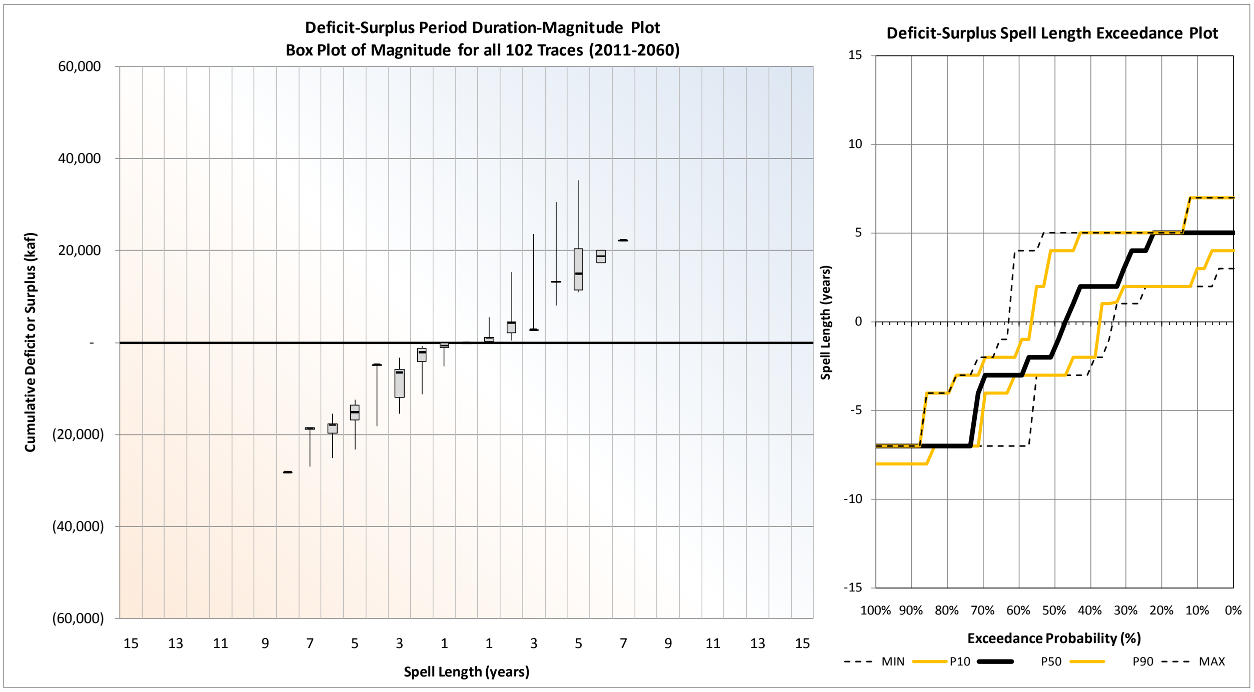
FIGURE B-23
Simulated Monthly Colorado River at Lees Ferry Natural Flow Statistics for 102 Realizations, 2011-2060
Figure shows the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



Another measure of the inter-annual variability and persistence of streamflow states (wet and dry) is characterized by determining the frequency, duration, and magnitude of deficit and surplus periods. Recall that for the purpose of this report, "deficit" is defined as a consecutive 2-year period when the mean is less than the observed long-term mean of 15.0 maf. Similarly, "surplus" is defined as a consecutive 2-year period when the mean is above 15.0 maf.

Figure B-24 illustrates four characteristics of deficit and surplus spells throughout the Study period (2011-2060): spell length, spell magnitude, the frequency of specific spell lengths occurring, and the relationship between deficits and surpluses in the scenario. Box plots displaying spell length are shown in the left figure (deficit, below the X-axis, and surplus, above the X-axis). The exceedance plot shown in the right figure displays the exceedance probabilities for spell lengths. Probabilities for deficit spells are shown in the bottom half of the plot. Probabilities for surplus spells are shown in the top half of the plot.

FIGURE B-24
Simulated Deficit and Surplus Spell Length and Magnitude for all 102 Realizations in the Observed Resampled Scenario
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



Spell length: the maximum deficit is 8 years (note that this length would be 11 years if the observed record extended through 2010), while the maximum surplus is 7 years. This information is provided in both the box plots and the exceedance plot.

Spell magnitude: referring to the box plots, the magnitude of the maximum deficit and surplus is about 27 maf and 22 maf, respectively. Deficit or surplus intensity can be computed by dividing the spell magnitude by the spell length.

Frequency of specific spell lengths occurring: the exceedance plot inset provides information regarding the frequency of the length of deficit and surplus spells. As such, the median exceedance probability of a deficit spell of 5 years is about 70 percent, meaning there is about a 30 percent chance of being in a deficit longer than 5 years. Similarly, at the 30 percent median exceedance probability is a surplus spell of 3 years, meaning there is about a 30 percent chance of being in a surplus period lasting more than 3 years.

Relationship between deficits and surpluses in the scenario: the median 50 percent exceedance probability corresponds to a deficit of 3 years. This result indicates that under the Observed Resampled scenario, there is a greater probability of being in a deficit (lasting at least 3 years) than in a surplus period.

6.0 Future Supply under the Paleo Resampled Scenario

6.1 Methods

The Paleo Resampled scenario is generated by applying the ISM to paleo- reconstructed streamflow data (762-2005) to develop 1,244 traces, each 50 years in length. The major strength of this method is the ability to produce sequences with magnitudes and deficit/surplus spells not found in the Observed Resampled scenario. In addition, as is true for the Observed Resampled scenario methodology, this method is based on measured data. While there is a wealth of literature documenting the strong link between streamflow and tree-ring growth in moisture limited regions, the exact magnitudes of a paleo reconstruction are not as reliable as historical flow data, particularly at the extremes, e.g. at the higher and lower flows (Woodhouse and Brown, 2001). This is attributed to a variety of factors in the reconstruction process, such as model selection to relate tree-ring width to streamflow. Furthermore, since ISM sequentially resamples the paleo record to generate hydrologic sequences, the sequences will only consist of flow magnitudes and sequences that are present in the paleo record, with the exception of the sequences created as a result of the wrap. The inclusion of the paleo conditioned scenario addresses this issue and the weakness of the paleo record in capturing magnitudes at the extremes.

As the paleo flow data are only available at the annual time-step for a single location (Lees Ferry, Arizona), annual flows at this location were disaggregated, spatially and temporally, throughout the Upper Basin natural flow locations using a nonparametric disaggregation method (Nowak et al., 2010). The disaggregation method relies on the observed record to model the spatial and temporal distribution properties of the monthly and annual flow. Disaggregated flows at the Lower Basin natural flow locations are generated by selecting an “analogue” year from the observed record. For a more detailed explanation of these methods please see Appendix N of the Interim Guidelines Final EIS and Nowak et al., 2010.

6.2 Results

The results for the Paleo Resampled scenario are presented as summary figures for annual and monthly flows for the Colorado River at Lees Ferry in Figures B-25 through B-28. As with the Observed Resampled scenario, multiple realizations are simulated producing a range associated with the flow statistics. Figure B-25 displays all of the individual 1,244 sequences in the Paleo Resampled scenario. The sequence bolded in Figure B-25 also appears in Figure B-26, which is a statistical summary of the 1,244 sequences. Figure B-26 depicts the annual range of natural flows, while Figure B-27 provides the annual statistics.

Annual natural flows are generally in the range of 3 - 25 maf, with a mean of approximately 14.7 maf. The minimum annual flow is much lower than the Observed Resampled scenario, while the maximum annual flow is similar. Conversely, the standard deviation is smaller than the Observed Resampled scenario, suggesting that a greater number of traces are closer to the mean value. In the Paleo Resampled scenario, the skew is slightly negative (as compared to slightly positive in the Observed Resampled scenario), suggesting a greater frequency of wet years than dry years (as compared to the Observed Resampled scenario). Finally, the backward lag correlation is slightly higher than the Observed Resampled scenario, suggesting a greater year-to-year correlation than in the observed record. The latter is likely inherent to the reconstruction techniques and relatively few reconstructions in the distant past.

FIGURE B-25
Colorado River at Lees Ferry Natural Flow for 1,244 Sequences for the Paleo Resampled Scenario

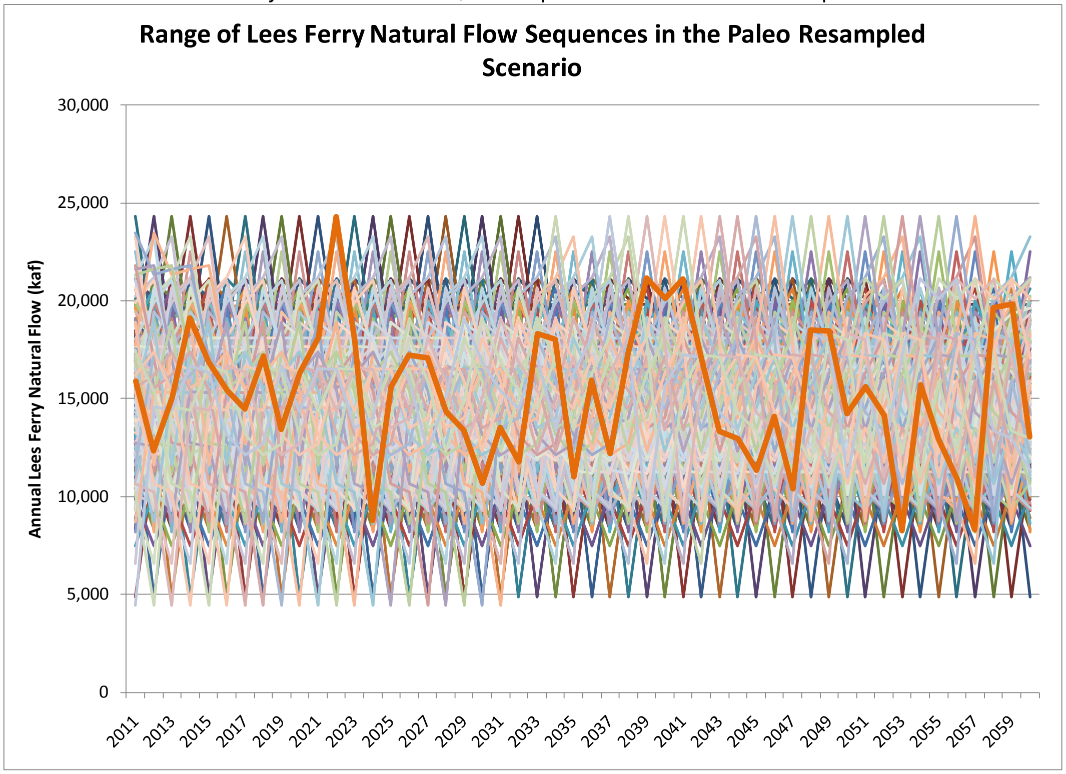


FIGURE B-26
Simulated Annual Colorado River at Lees Ferry Natural Flow Statistics for 1,244 Traces, 2011-2060
Figure shows the median (line), 25th – 75th percentile band (dark shading), 10th – 90th percentile band (light shading), max/min (whiskers), and a representative trace (line).

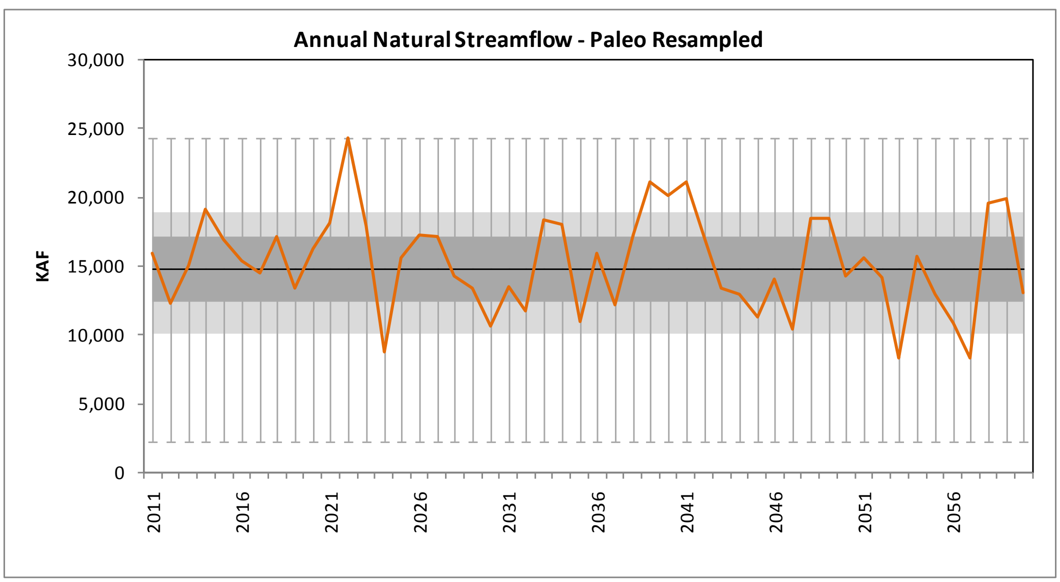
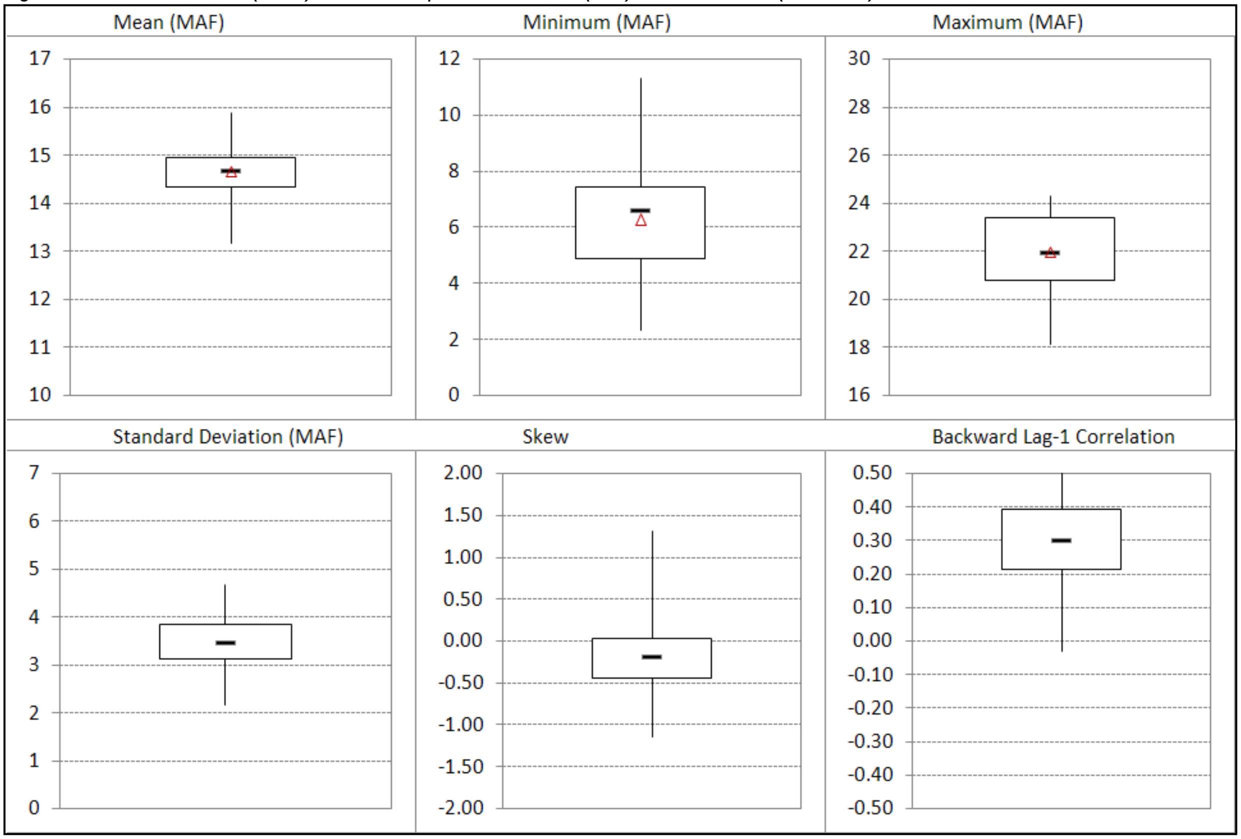


FIGURE B-27
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for the Paleo Resampled Scenario
Figure shows the median (dash), 25th – 75th percentile band (box), and max/min (whiskers).



Monthly river flows do not suggest a significant change from the Observed Resampled scenario. Peak flows occur in late spring with May, June, and July exhibiting the highest flows (Figure B-28). As in the Observed Resampled scenario, June flows are both the highest and most extreme, with mean monthly flows averaging about 4 maf/month and ranging from about 1-9 maf/month. This was expected as the disaggregation applied to the annual paleo reconstruction was trained on the observed natural flow data. Also similar to the Observed Resampled scenario, late summer and fall flows are considerably lower and exhibit significantly less variability.

FIGURE B-28
Simulated Annual Colorado River at Lees Ferry Natural Flow Statistics for 1,244 Realizations, 2011-2060
Figure shows the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).

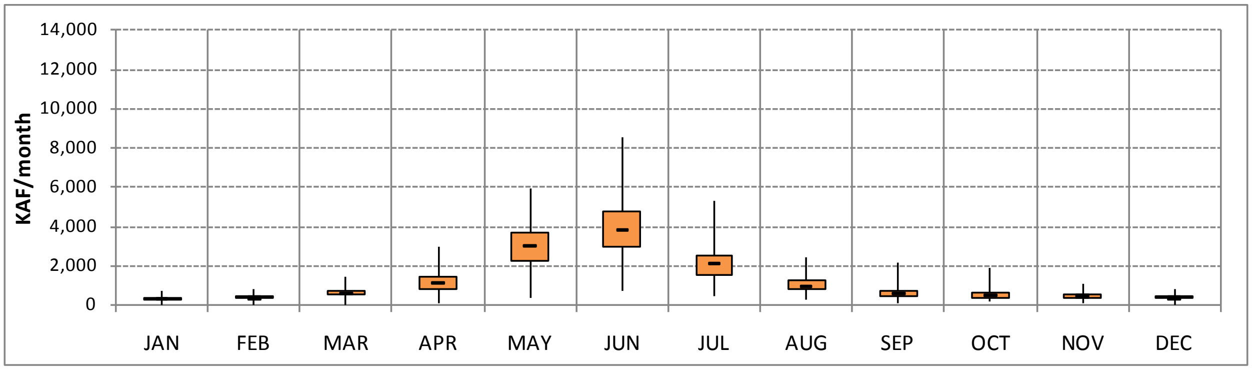
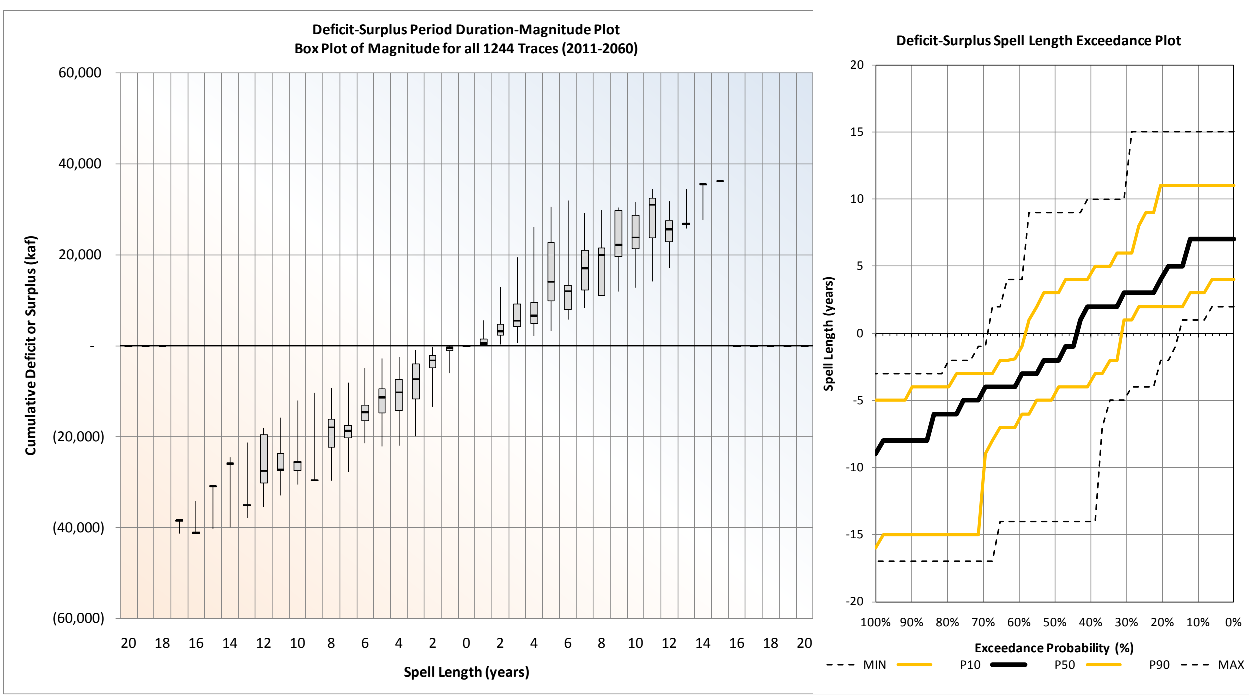


Figure B-29 illustrates the length, magnitude, and frequency of deficit and surplus spells. Under the Paleo Resampled scenario, maximum deficit and surplus periods are significantly longer in duration than those in the Observed Resampled scenario. Maximum deficit spell length under the Paleo Resampled scenario is about 17 years, while the maximum surplus spell length is about 15 years. The 17-year deficit period contains approximately 30-40 maf of total deficit. For comparison, the current deficit has persisted for 11 years (through 2010) with an accumulated deficit of about 32 maf. Thus, from a measure of deficit intensity, while the deficit is sustained longer in the Paleo Resampled scenario, the annual deficits are not dissimilar from the Observed Resampled scenario.

FIGURE B-29
Simulated Deficit and Surplus Spell Length and Magnitude for all 1,244 Realizations in the Paleo Resampled Scenario
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



7.0 Future Supply under Paleo Conditioned Scenario

7.1 Methods

The Paleo Conditioned scenario is generated by applying a non-parametric technique to "blend" the observed historical and paleo- reconstructed records to generate 1,000 traces, each 50 years in length. flow magnitudes vary significantly across multiple reconstructions for a particular site (Stockton and Jacoby, 1976; Hildalgo et al., 2000; Hirschboeck and Meko, 2005; and Woodhouse et al., 2006). However, the paleo hydrologic state agreement (i.e., wet or dry) is quite reliable across different reconstructions (Woodhouse et al., 2006).

The paleo- conditioned technique blends the rich variety of drought/surplus found in the paleo reconstruction with reliable magnitudes from the observed natural flow data by first extracting a sequence of years represented simply as wet or dry from the streamflow reconstruction. Flow magnitudes are then conditionally resampled from the observed record for each year in the sequence, based on the current and previous hydrologic state. Thus, any underlying relationship between magnitude and sequencing is preserved while circumventing issues associated with magnitude reliability. For example, if an observed flow value occurred as the first year of a drought, it can only be assigned to a "dry state year" that was preceded by a "wet state year" as part of a paleo conditioned trace. Similarly, if an observed flow magnitude was the second year of a multi-year surplus period, that value can only be assigned to a "wet state year" that was preceded by another "wet state year." This logic holds true for all wet/dry sequencing combinations. Following this method, a wealth of traces can be generated (at least 1,000 are recommended to limit sample variability) by simply changing the initial wet/dry sequence information extracted from the paleo data. Different from the ISM technique, the number of sequences is not limited to the length of the streamflow record being resampled. For a more detailed explanation of the method, see Appendix N of the Interim Guidelines Final EIS and Prairie et al., 2008. As was the case with the Paleo Resampled scenario, the Paleo Conditioned scenario introduces considerable variability when compared with the observed data, yet maintains the reliability of the observed magnitudes. paleo conditioned traces were also generated at the annual time-scale for Lees Ferry and required the same disaggregation process employed for the Paleo Resampled scenario in order to produce monthly data at multiple locations.

7.2 Results

The results for the Paleo Conditioned scenario are presented as summary figures for annual and monthly flows at Colorado River at Lees Ferry in Figures B-30 through B-33. Figure B-30 displays all of the individual 1,000 sequences in the Paleo Conditioned scenario. The sequence bolded in Figure B-30 also appears in Figure B-31, which is a statistical summary of the 1,000 sequences. Figure B-31 depicts the annual range of natural flows, while Figure B-32 provides the annual flow statistics.

Annual natural flows are generally in the range of 5-25 maf, with a mean of approximately 14.9 maf. The annual statistics are similar to the Observed Resampled scenario, largely due to the paleo- conditioned technique that borrows the magnitudes from the observed record when combining with state information from the paleo reconstructions. Similarly, the standard deviation, skew, and backward lag correlation indicate that the annual flow statistics are similar to the Observed Resampled scenario. Monthly flows are also similar in pattern and magnitude to the Observed Resampled and Paleo Resampled scenarios as shown in Figure B-33.

FIGURE B-30
Colorado River at Lees Ferry Natural Flow for 1,000 Sequences for the Paleo Conditioned Scenario

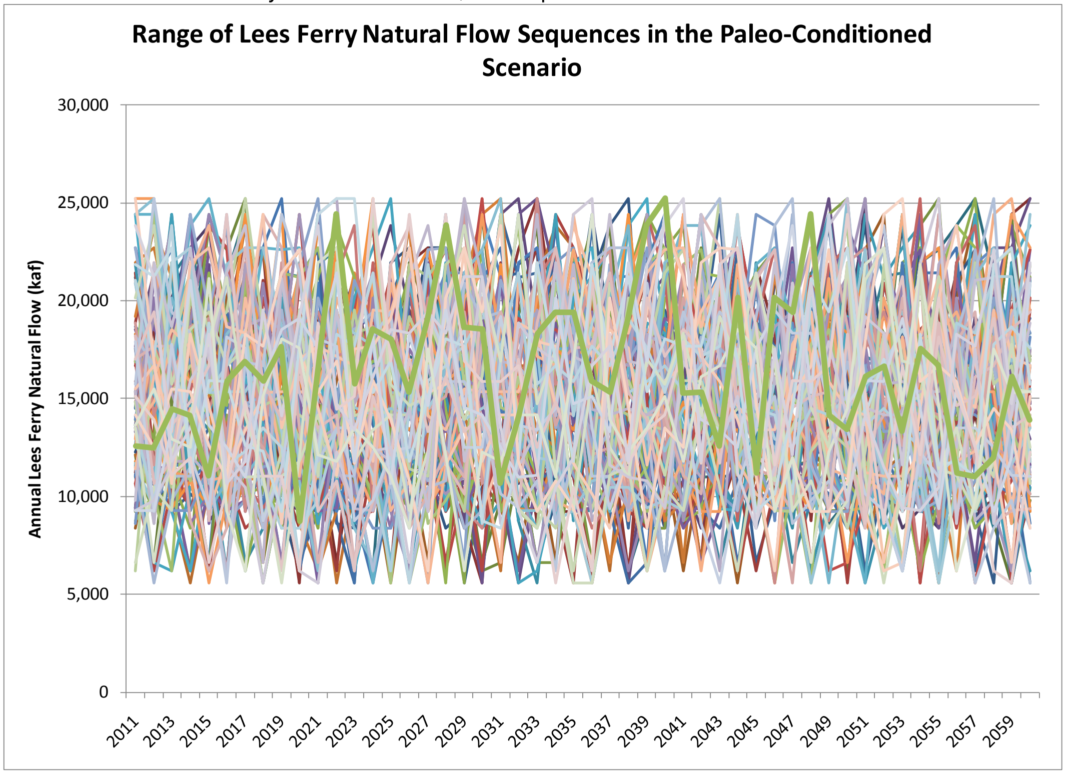


FIGURE B-31
Simulated Annual Colorado River at Lees Ferry Natural Flow Statistics for 1,000 Realizations, 2011-2060
Figure shows the median (line), 25th – 75th percentile band (dark shading), 10th – 90th percentile band (light shading), max/min (whiskers), and a representative trace (line).

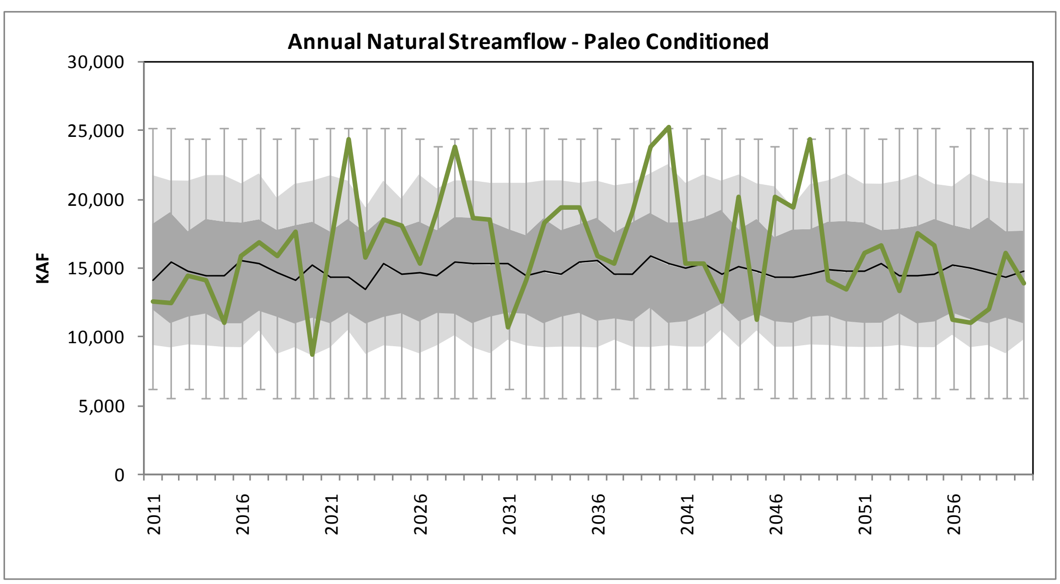


FIGURE B-32
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for the Paleo Conditioned Scenario
Figure shows the median (dash), 25th – 75th percentile band (box), and max/min (whiskers).

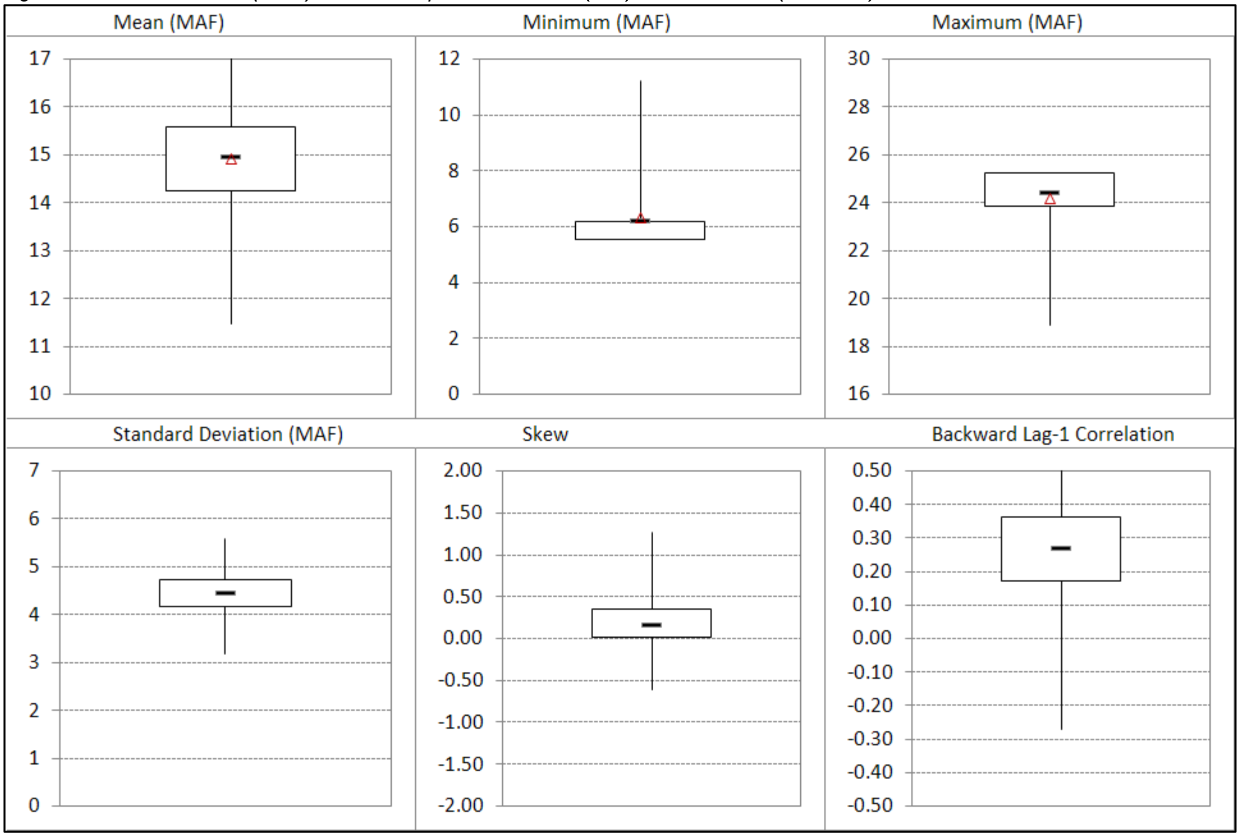
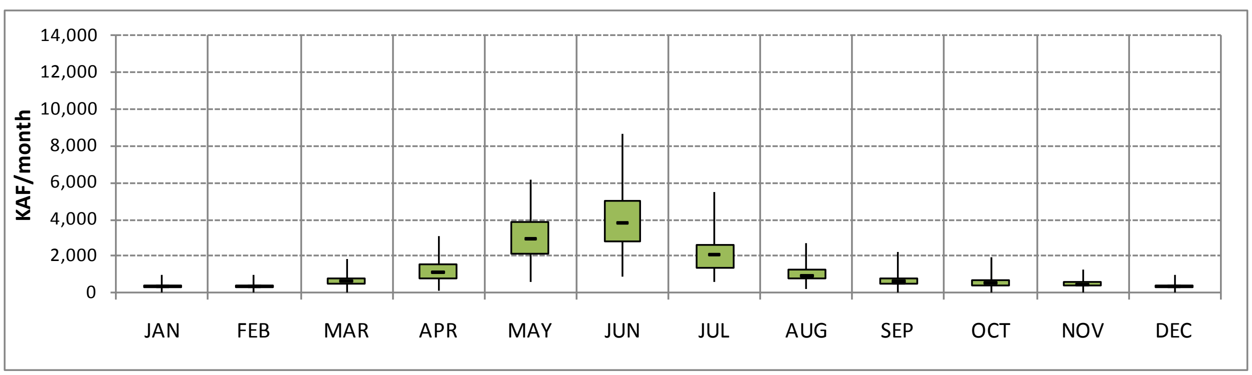
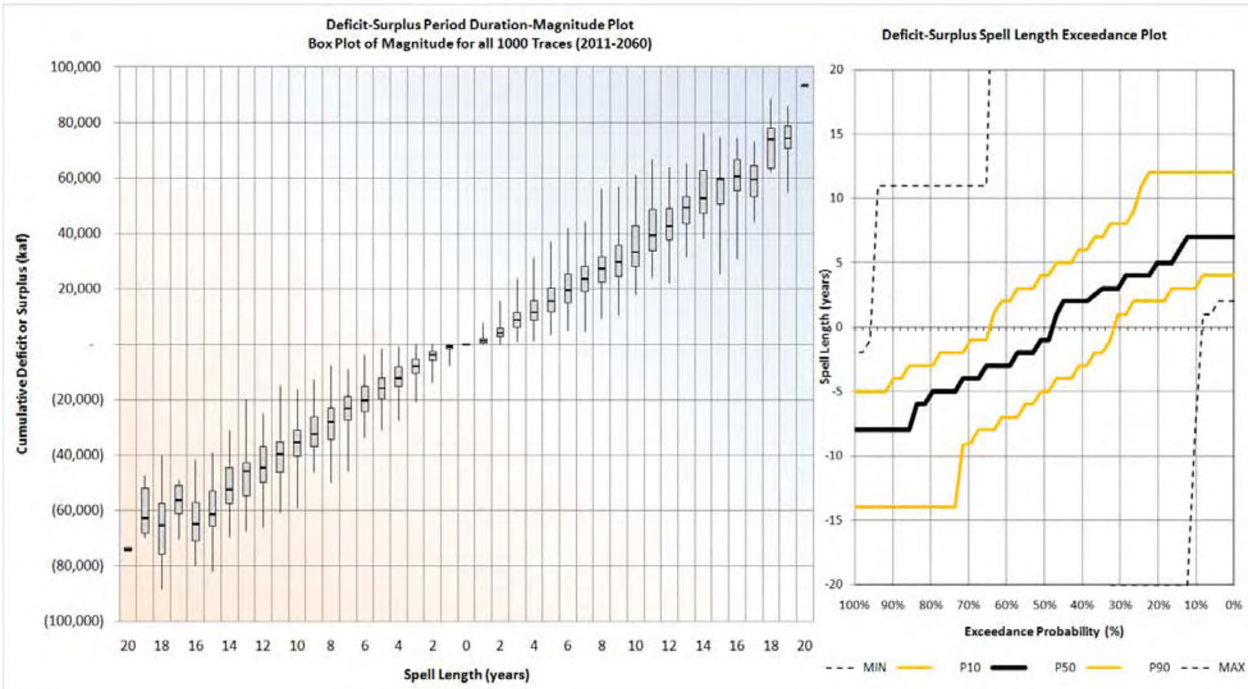


FIGURE B-33
Simulated Annual Colorado River at Lees Ferry Natural Flow Statistics for 1,000 Realizations, 2011-2060
Figure shows the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



The most significant difference between the Paleo Conditioned scenario and the Observed Resampled and Paleo Resampled scenarios is in the inter-annual variability and persistence of streamflow states (wet and dry). Figure B-34 illustrates the frequency, length, and magnitude of deficit and surplus spells. Deficit periods 15 years or longer are observed in this scenario and produce accumulated deficits greater than 60 maf. Similarly, extended surplus periods of similar length produce surpluses greater than 60 maf. Under this scenario, deficit periods could persist considerably longer than the Observed Resampled and produce deficits almost twice as large. Interestingly, however, the median probability of exceeding a deficit spell of greater than 7 years is only 20 percent, and there is only a 10 percent likelihood of exceeding a 5-year surplus period.

FIGURE B-34
Simulated Deficit and Surplus Spell Length and Magnitude for all 1,000 Realizations in the Paleo Conditioned Scenario
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



8.0 Future Supply under the Downscaled GCM Projected Scenario

8.1 Methods

Future changes in climate variability and trends, and their influence on streamflow and Colorado River Basin water supply, have been studied by several researchers in recent years and GCM future projections indicate that the climate may exhibit trends and increased variability over the next 50 years beyond what has occurred historically. The Downscaled GCM Projected scenario is one representation of this plausible future condition.

A number of methods for incorporating climate information in planning studies are available and have been summarized by Reclamation (2007) and others (Hamlet et al., 2010). Methods range from simple adjustments to the temperature and precipitation inputs (Delta method), to application of regional climate models for weather generation, to bottom-up risk-based approaches targeting system vulnerabilities. No one approach is better than the other, but rather, each serves a specific planning purpose and set of analysis tools. The approach taken in the Study incorporates future climate information from GCMs, subsequently bias-corrected and statistically downscaled, to drive a hydrologic model of the Colorado River

Basin. The hydrologic model simulates the effects of future climate on hydrologic processes in the Basin and provides information relating to streamflow at all major inflow points to the Colorado River and tributaries. The streamflow and ET information is then used as input into the systems model (CRSS), Reclamation's primary Basin-wide simulation model used for long-term planning studies. This approach is shown graphically in Figure B-35. Using this approach of linking global and regional climate information, physically-based hydrologic processes, streamflow routing, and systems modeling allow for a consistent linkage between climate and system responses that are desired as part of this scenario and the overall study of future Basin reliability.

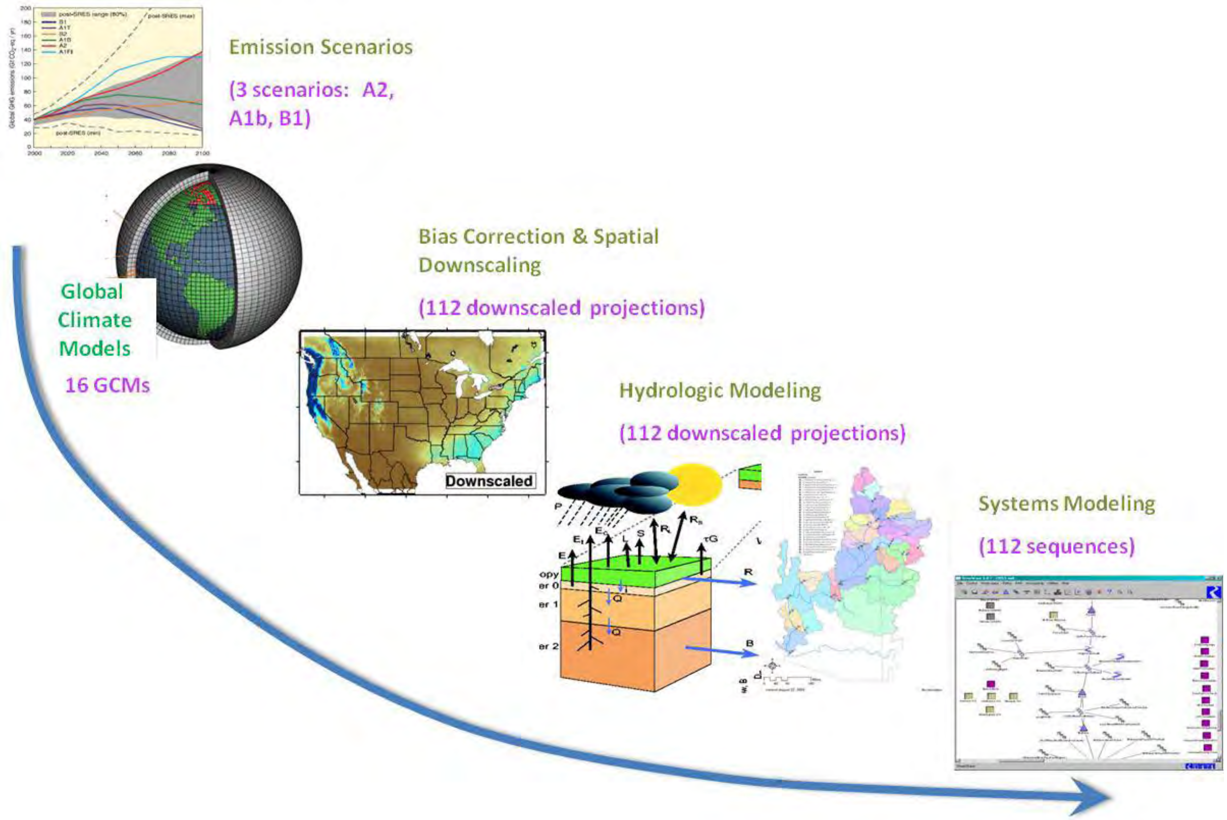
The methodological approach to develop the Downscaled GCM Projected scenario consists of five major elements depicted graphically in Figure B-35. The result of this approach is 112 unique sequences of natural flow under future climate projections. A total of 112 future climate projections used in the Intergovernmental Panel on Climate Change Fourth Assessment Report, subsequently bias corrected and statistically downscaled, were obtained from the Lawrence Livermore National Laboratory under the World Climate Research Program's Coupled Model Intercomparison Project Phase 3 (Maurer et al., 2007) [7]. This data was incorporated in the first three elements of the approach in Figure B-35.

A methodological approach similar to that taken to develop the Downscaled GCM Projected scenario was also taken to develop the results featured in the March 2011 report to Congress released to respond to requirements of the SECURE Water Act (SECURE Report) (Reclamation, 2011). The SECURE Report was prepared by Reclamation's Office of Policy and Administration and includes projections of how climate change may impact the water supply on the Colorado River Basin. The SECURE Report was prepared by Reclamation to provide consistent, reconnaissance-level information focused on the future risks to water supply throughout the eight Reclamation basins.

Some differences exist, however, with respect to the methodological approach taken to generate the results in the SECURE Report. The methodological differences consist primarily of the application of a different technique to generate daily weather forcings. Although a secondary bias- correction has not been applied to the results presented here, the investigation of such a correction is ongoing and will be applied (and reported in a subsequent interim report), resulting in another methodological difference. Reporting differences consist of the selection of baseline climate conditions and the future analysis period. Specifically, the SECURE Report computes future decadal changes from a 1991-2000 baseline condition, whereas the change statistics reported here are computed between the long-term record and the Study period of 2011-2060. Therefore, results between the Study and the SECURE Report are not identical; however, ongoing work in the Study will be used to inform future reports under the SECURE Water Act.

[7] This data is available via the Web site, Bias Corrected and Downscaled World Climate Research Program Coupled Model Intercomparison Project Phase 3 Climate Projections (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/), which is jointly hosted by the Green Data Oasis, Santa Clara University, Reclamation, and Lawrence Livermore National Laboratory.

FIGURE B-35
Methodological Approach for the Development of the Downscaled GCM Projected Scenario



8.1.1 Emission Scenarios

Special Report on Emissions Scenarios (SRES), Emission Scenarios A2 (high), A1B (medium), and B1 (low), were selected to drive 16 different GCMs. The A2 Scenario is representative of high population growth, slow economic development, and slow technological change. It is characterized by a continuously increasing rate of greenhouse gas (GHG) emissions, and features the highest annual emissions rates of any scenario by the end of the 21st-Century. The A1B Scenario features a global population which peaks mid century, and rapid introduction of new and more efficient technologies balanced across both fossil- and non-fossil-intensive energy sources. As a result, GHG emissions in the A1B Scenario peak around mid century. Last, the B1 Scenario describes a world with rapid changes in economic structures toward a service and information economy. GHG emission rates in this scenario peak prior to mid century, and are generally the lowest of the scenarios.

Assumptions related to parameter characteristics included in the SRES Emission scenarios (e.g., high population growth, slow economic development, etc.) are not related to parameter characteristics of the Water Demand scenarios (see *Technical Report C – Water Demand Assessment*). However, due to the approach being taken in the Study to combine all water supply scenarios with all water demand scenarios, water demand scenarios will inevitably be paired with water supply scenarios derived from SRES emission scenarios that have similar assumptions regarding parameter characteristics. Also, when considering water demand scenarios combined with water supply scenarios that incorporate climate change, agricultural water demands will be modified to reflect estimates of changes in ET rates consistent with the assumptions for water supply.

8.1.2 GCMs

Sixteen GCMs were coupled with the three emissions scenarios to simulate the global atmosphere and oceans and provide projections of specific climatological forcings (principally temperature and precipitation) during the period from 1950-2099. Many of the GCMs were simulated multiple times for the same emission scenario due to differences in starting climate system state; thus, the number of available projections (112) is greater than simply the product of the number of GCMs and emission scenarios. Appendix B5 provides a summary of the GCMs, initial conditions, and emissions scenario combinations featured in the Study. The subsequent results presented on future climate (primarily temperature and precipitation) rely on the data generated by these GCMs.

8.1.3 Bias Correction and Spatial Downscaling (BCSD)

Due to the coarseness of the GCM grids and inherent biases in their results, the GCM results are transformed to a local scale (~12 km) through a process called bias correction and spatial downscaling (BCSD). The methods of this process are described in detail in Wood et al., 2002; Wood et al., 2004; and Maurer, 2007.

The purpose of bias correction is to adjust a given climate projection for inconsistencies between the simulated historical climate data and observed historical climate data. In the BCSD approach, projections are bias corrected using a quantile mapping technique. Following bias correction, the adjusted climate projection data are statistically consistent (monthly cumulative distribution functions are identical) with the observed climate data for the historical overlap period of 1950-1999. Beyond the historical overlap period (i.e., 2000-2099), the adjusted climate projection data reflect the same relative changes in mean, variance, and other statistics between the future (2000-2099) and historical periods (1950-1999). Note that this methodology assumes that the GCM biases have the same structure during the 20th and 21st-Centuries' simulations.

Downscaling spatially translates bias-corrected climate data from the coarse, 2-degree (~200 kilometer), spatial resolution typical of climate models to a Basin-relevant resolution of 1/8th degree (12 kilometers), which is more useful for hydrology and other applications. The spatial downscaling process generally preserves observed spatial relationships between large- and fine-scale climate. This approach assumes that the topographic and climatic features that determine the fine-scale distribution of large-scale climate will be the same in the future as in the historical period.

8.1.4 Hydrologic Modeling

The resulting BCSD temperature and precipitation monthly forcings are further disaggregated into daily patterns, borrowing from the historical period for reference conditions. The monthly statistics of the historical period are retained in this process. This daily set of forcings is then used as input to the VIC hydrologic model to generate streamflow. For each of the 112 climate projections, VIC is simulated and produces a distinct trace of natural flows at each of the 29 natural flow locations.

Developed at the University of Washington, the VIC model is a semi-distributed, macro-scale hydrologic model that solves the water balance at each model grid cell. A VIC model of the Colorado River Basin was previously developed by the University of Washington (Christensen and Lettenmaier, 2009). A thorough description of the VIC model is provided in Appendix B4. This model was provided to Reclamation for the purpose of further calibration and analysis, and all operation of the model for the Study was conducted by the subconsultant, AMEC Earth & Environmental.

Bias correction will be applied to the VIC-simulated flows to account for any systematic bias in the hydrology model or data sets. Currently under investigation is the most appropriate bias-correction scheme to implement given offsetting biases between the VIC validation period and the overlapping climate projection period; this remains an ongoing task. The flows presented in this report are considered “raw” in that no streamflow bias correction is included.

In addition to producing routed natural flows, the VIC model also provides output for other water supply indicators, including precipitation, runoff, baseflow, ET, soil moisture, and SWE. The subsequent results presented on hydrologic processes rely on these parameters generated by the VIC model.

Additional detail on VIC and its application for the Study can be found in Appendices B4 and B5. Ongoing development of documentation describing the complete VIC calibration and validation process will be provided in Interim Report No. 2.

8.1.5 Systems Modeling

A total of 112 realizations at the 29 natural flow locations are taken from the VIC model simulations. Differing from the three other future water supply scenarios, each Downscaled GCM Projection hydrologic sequence of streamflow will likely exhibit a long-term future trend and increased variability beyond what occurred historically. For the Study, no differentiation is applied for each of the sequences, based on emission scenario or historical GCM skill. In essence, each of the 112 sequences is treated as equally likely when applied in CRSS in later phases of the Study. From a mechanical standpoint, the Downscaled GCM Projected scenario is implemented as 112 distinct projections of the future, each starting in the year aligned with the Study period start year of 2011.

8.2 Uncertainty

The process outlined above and shown graphically in Figure B-35, in which climate projections are used to generate projections of future streamflow, contains a number of areas of uncertainty. Each step in the process contains uncertainty and it is important to recognize these in the interpretation of results. First, emission scenarios describing the global emissions of GHGs over the century are used as the primary input to GCMs. The SRES emission scenarios are used to project a range of future global development pathways. Each emission scenario is considered plausible, but the fact that the range may not be sufficiently broad cannot be ruled out. In addition, the climate system responds to a number of factors that contribute to radiative forcings affecting the warming of earth’s surface. Factors such as aerosols, solar activity, surface albedo, and variations in the earth's orbit, all influence the earth's energy balance. These mechanisms are included in the climate models to the degree they are understood and can be projected into the future, but represent an inherent uncertainty in attempting to simulate the global climate system on decadal and century scales. Anthropogenic carbon dioxide emissions, which are directly represented in the emission scenarios, are believed to represent the largest component of the estimated radiative forcing (Intergovernmental Panel on Climate Change, 2007).

Second, GCMs are used to simulate global climate patterns resulting from atmospheric forcings and feedbacks throughout the land, ocean, and atmosphere interactions. The GCMs are still applied at relatively coarse scales in relation to what is required for watershed assessments, and therefore are not likely to capture important regional phenomena. Much of the uncertainty in climate projections through mid century is associated with the GCMs, rather than emission scenarios. The GCM results are necessarily bias-corrected and spatially downscaled to be useful at the watershed scale. These bias correction and downscaling processes, while necessary, remove some of the physical linkages from the climate projections and introduce an aspect of further uncertainty. High resolution regional climate modeling may help resolve some of the scale mismatch (both spatially and temporally) in the future, but the availability of these simulations over a broad ensemble of models and emission scenarios is limited.

Finally, hydrologic models are approximations of the complex physical processes that occur on the watershed scale. The VIC model is considered a strong, physically based hydrology model, but simulates hydrologic processes at the macro scale. The model necessarily needs to parameterize certain aspects of the hydrologic cycle to capture the effects at smaller scales. Several assumptions in the VIC modeling approach carry considerable uncertainty. First, the VIC modeling assumes that land use and vegetative cover are fixed throughout the simulation period. At present, future assumptions of land use that are consistent with the socioeconomic assumptions in the water demand scenarios have not been integrated into the water supply scenarios. Changes in climate are likely to drive changes in natural species (vegetative and aquatic) distribution and these will influence future hydrologic processes and streamflow. The magnitude of these impacts are believed to be relatively small compared to the effects of changes in direct temperature and precipitation; however, the magnitude has not yet been quantified. Further investigation as to the relative effects of these changes will be addressed in future work.

In addition, the VIC model, as described in this report, has been adopted without re-calibration. Results appear reasonable at the larger watershed scale but there is observed bias in particular watersheds and at the sub-watershed scale. Work is ongoing to further diagnose and address these issues.

8.3 Results

The results of the 112 future climate projections are presented in this section. The results are presented for climate, hydrologic processes, and streamflow. Climate teleconnections are briefly discussed as work is ongoing in this area and will be provided in Interim Report No. 2. For climate, results are presented in terms of annual precipitation and temperature trends followed by an analysis of seasonal trends. For hydrologic processes, results are presented for ET, snowpack, soil moisture, and runoff. Both annual and seasonal analyses are presented. The last section of the results focuses on projected changes in streamflow, both annual and seasonal, and predominately at Lees Ferry. For all results, supplemental figures for additional Basin areas are provided in Appendix B7.

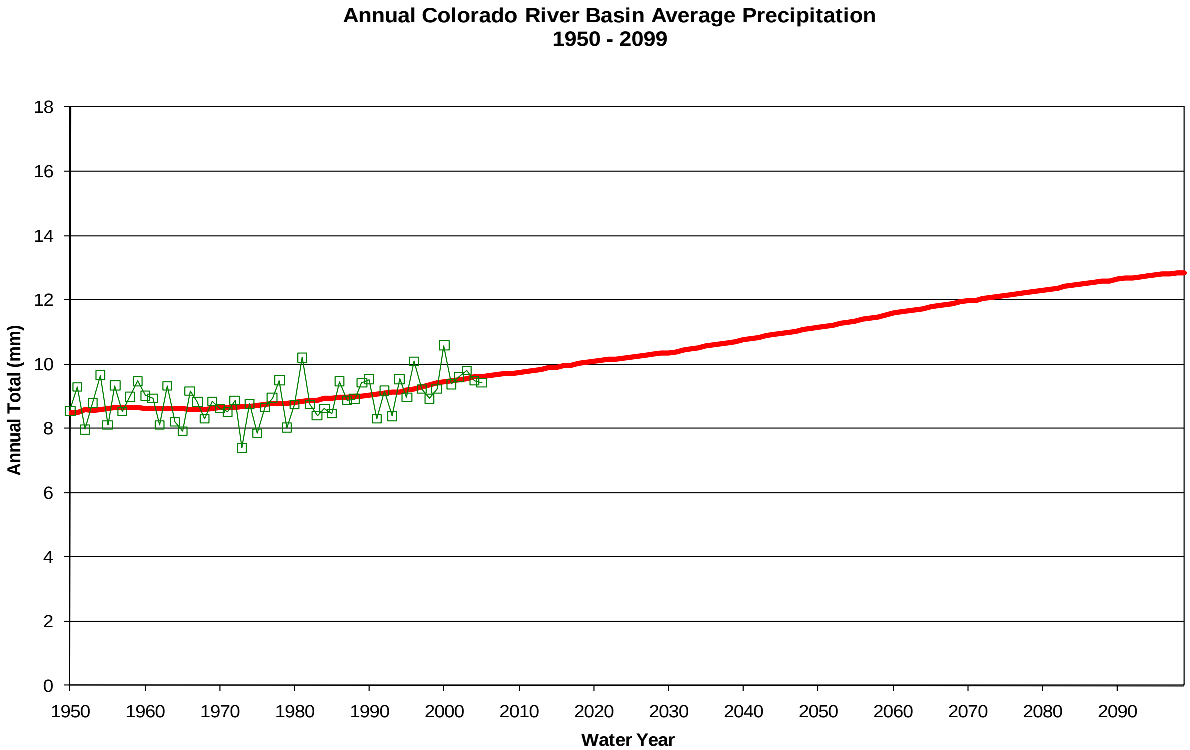
Climate and hydrologic process results are presented as changes from the most current 30-year climatological period as described by NOAA (1971-2000) to three future 30-year periods (2011-2040, 2041-2070, and 2066-2095). Thirty-year periods were chosen to span the almost 90-year future projection period (2011-2099) with a manageable number intervals. In addition, due to the difference in initial atmospheric-ocean conditions between the GCMs, a 30-year period is sufficient to separate projected average conditions from individual and multi-year variability. For simplicity, these periods are referred to as the year in which they are centered, i.e., 1985, 2025, 2055, and 2080.

Although the Study period is through 2060, the 112 future climate projections extend through 2099. The additional approximate 40 years of projections have been included in the analyses for the climate and hydrologic processes results, as they offer additional insight into the projected changes of these parameters. To facilitate a more direct comparison with the projected streamflow from the other three scenarios (Observed Resampled, Paleo Resampled, and Paleo Conditioned), streamflow results are presented through 2060.

8.3.1 Climate

Climate projections from the 112-projection ensemble indicate a strong continued warming throughout the Colorado River Basin. Figure B-36 shows the Basin average temperature and precipitation projections for 1950-2099 (the length of the GCM projection period) in relation to the 1950-2005 (the length of the observed climate period) historical observed climate. The projection ensemble indicates substantial warming with a median increase in annual temperature of about 1.3ºC by 2025, 2.4ºC by 2055, and 3.3ºC by 2080. All projections are consistent in the direction of the temperature change, but vary in terms of climate sensitivity. Annual precipitation trends are not apparent in this Basin-wide analysis. Roughly half of the projections indicates a wetter future, while the other half indicates drier conditions. The uncertainty in future annual precipitation appears to be increasing with time, while the median of the projections is relatively unchanged.

FIGURE B-36
Historical (line series with markers) and Projected Annual Average Temperature (top) and Projected Annual Total Precipitation (bottom). Smoothed as a 10-year Mean.
Shading represents a range of projections and the solid line represents a median of projections.



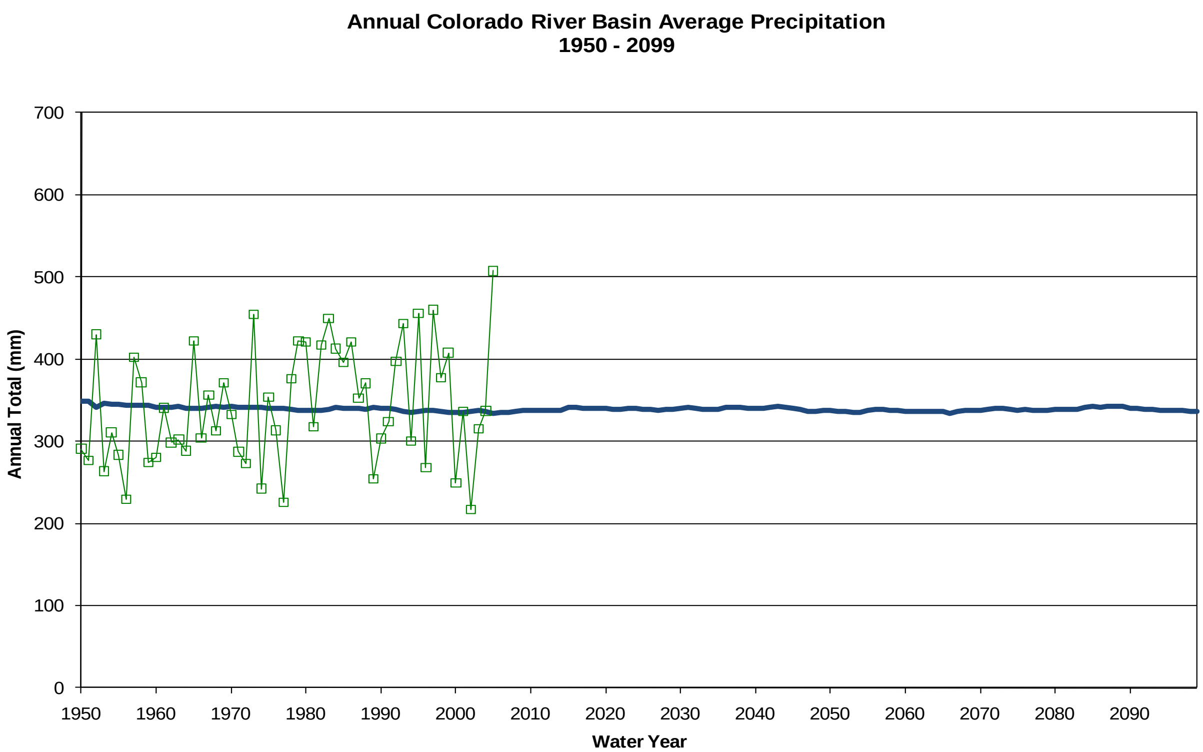
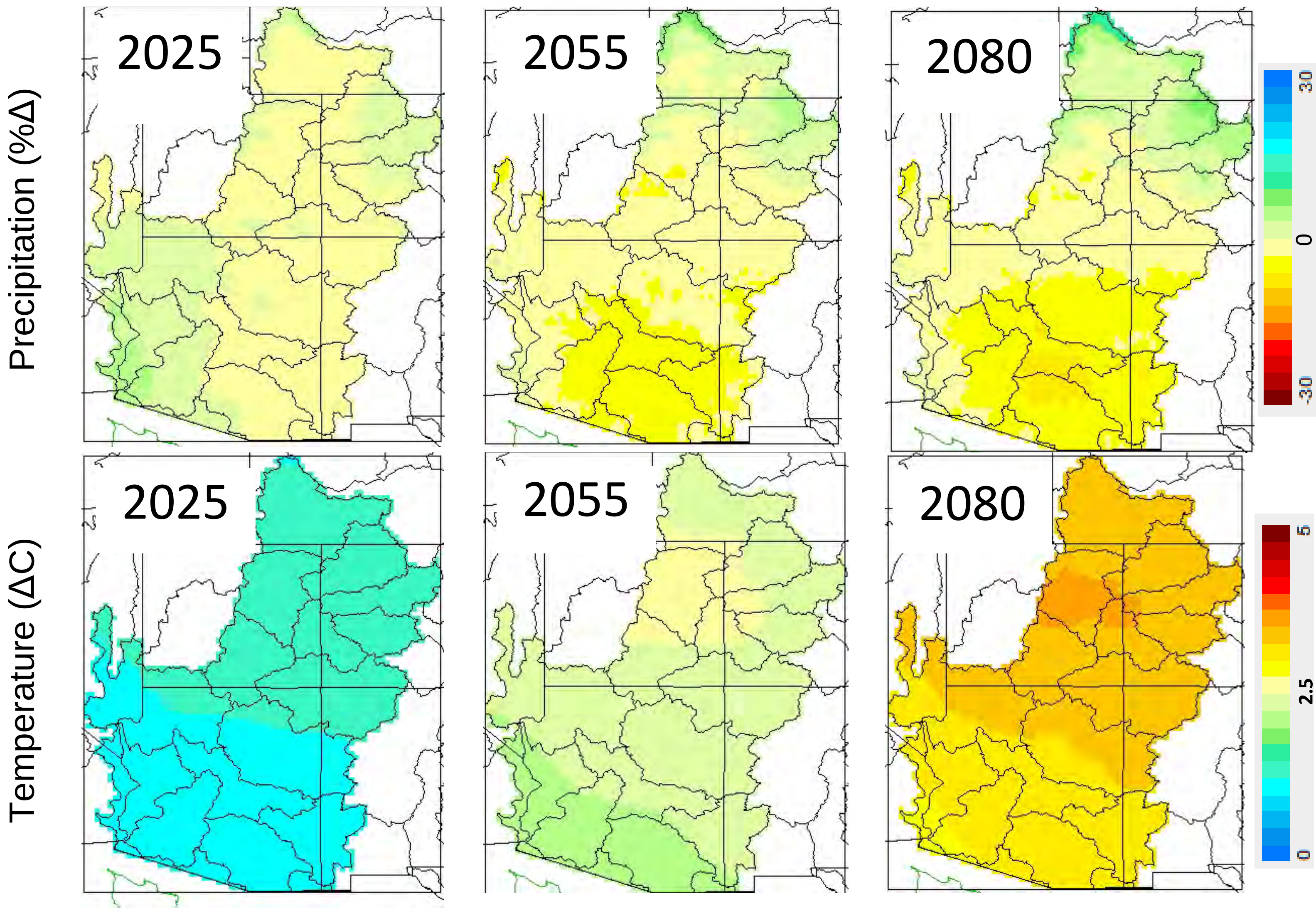


Figure B-37 presents the change in mean annual precipitation (percent change) and temperature (absolute change) for three future periods: 2011-2040 (2025); 2041-2070 (2055); and 2066-2095 (2080), relative to the 30-year historical period 1971-2000 (1985). Projected precipitation changes are relatively modest in 2025. However, by the 2055 and 2080 periods, precipitation decreases by up to 10 percent in much of Lower Basin. In contrast, precipitation increases by up to 10 percent in the Upper Basin with little geographic variation. For most of the Basin, temperature increases are within 1.0°C to 1.5°C, 2.0°C to 2.5°C, and 3.0°C to 4.0°C for 2025, 2055, and 2080, respectively.

FIGURE B-37
Mean Projected Change in Annual Precipitation and Temperature
2025 (2011-2040) versus 1985 (1971-2000); 2055 (2041-2070) versus 1985 (1971-2000); and 2080 (2066-2095) versus 1985 (1971-2000).



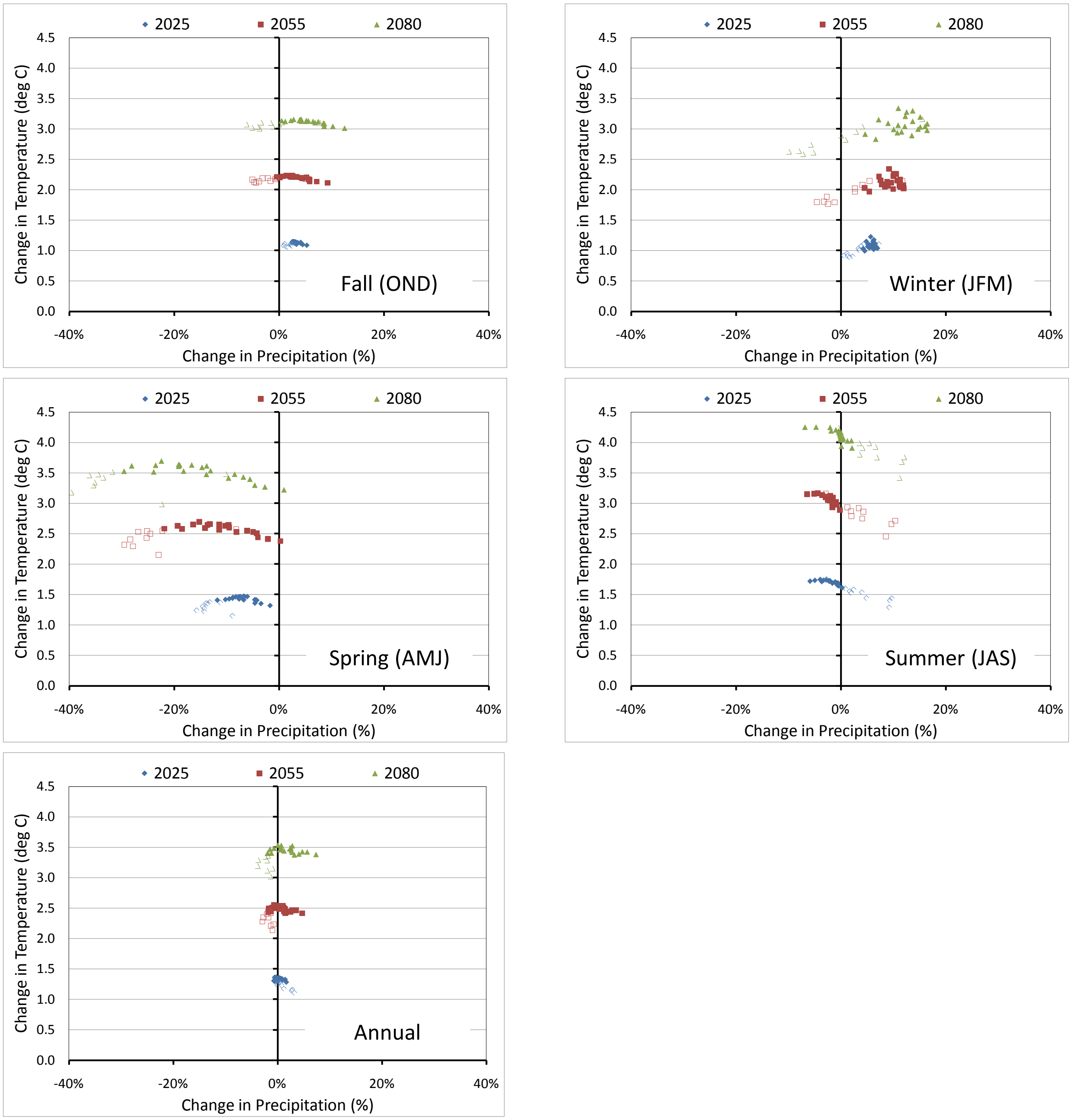
Maps of seasonal changes in temperature and precipitation for the three future 30-year periods are included in Appendix B7 and are summarized here.

The seasonal analysis shows that 2055 projected seasonal temperature changes exhibit minimal geographic variation in the fall. Winter and summer temperatures in the Upper Basin increase slightly more than those in the Lower Basin. Projected temperature increases are lowest in winter, ranging from 1.5°C to 2.5°C. The largest projected temperature increases occur in summer, and range from 2.5°C to 3.0°C.

The 2055 change in projected median winter precipitation is highly varied throughout the Basin, with values in the Lower Basin decreasing from 0 to 15 percent, while values in the Upper Basin increasing from 0 to 15 percent. During spring, precipitation is projected to decrease throughout the Basin. The most severe reductions (on a percentage basis) occur in the southwestern region, where the decline is up to 30 percent. Summer is the only season in which projected precipitation shows a greater decrease in the Upper Basin than in the Lower Basin. Trends in fall precipitation closely resemble those of the winter season, but the projected percent changes for fall are lower in magnitude.

Figure B-38 summarizes projected changes in climate conditions on a watershed basis as indicated by the 112-projection ensemble for the three future 30-year periods. Each point represents a single watershed (one for each contributing area) and the location of a point is determined by: the mean projected change in temperature between the future periods and the simulated historical period 1971-2000; and the mean projected change in precipitation between the future periods relative to the simulated historical period. Change in temperature is measured in degrees Celsius, while change in precipitation is measured as a percentage.

FIGURE B-38
Projected Changes in Mean Seasonal and Annual Temperature and Precipitation for the Colorado River Basin
Periods are 2025 (2011-2040); 2055 (2041-2070); and 2080 (2066-2095), compared to the 1985 (1971-2000) historical period(hollow symbols represent Lower Basin locations, while solid symbols indicate Upper Basin locations).



For a given season and future time period, projected changes in temperature are relatively consistent across all watersheds, with little variation throughout the Basin. By 2025, temperatures are projected to increase at least 1.0°C in nearly all watersheds for all four seasons. Spring and summer show the greatest warming, with seasonal temperatures in most watersheds increasing 3°C to 4°C by 2080. Annual temperature increases are projected at 1.0°C to 1.5°C, 2.0°C to 2.5°C, and 3.0°C to 3.5°C for 2025, 2055, and 2080, respectively.

Projected changes in seasonal precipitation vary widely among watersheds and among seasons. In general, precipitation variability increases with time. On an annual basis, projected precipitation through 2080 is generally within 5 percent of historical precipitation, with half of the Basin's watersheds exhibiting positive change and half exhibiting negative change. The most significant and monotonic change in precipitation occurs in spring, during which all watersheds show a decrease in precipitation for each of the future time periods. By 2080, the decrease in spring precipitation ranges from 0 to 40 percent with the values well distributed within the range. For fall, winter, and summer, there is no discernible trend in precipitation, in that all watersheds are well distributed between positive (about 20 percent for winter in 2080) and negative (about 10 percent for summer and winter in 2080) precipitation change in each future period.

Summary of Changes in Climate

- Warming is projected to increase across the Basin with largest changes in spring and summer and larger changes in the Upper Basin rather than the Lower Basin. Annual Basin-wide median temperature increases are projected to be approximately 1.3°C, 2.4°C, and 3.3°C for 2025, 2055, and 2080, respectively, with less warming in winter and higher warming in summer.

- Precipitation patterns continue to be spatially and temporally complex, but projected seasonal trends toward drying are significant in certain regions. Precipitation patterns are complex due to influence of oceans, storm tracks, changes in atmospheric circulation patterns (e.g., Hadley cell expansion), and the interplay with mountainous regions (orographic considerations). A general trend toward drying is present in the Basin, although increases are projected in the higher elevation and most hydrologically-productive regions. Consistent and expansive drying conditions are projected for the spring throughout the Basin. For much of the Basin, drying conditions are projected in the summer, although some areas of the Lower Basin are expected to see slight increases in precipitation which may be due to the monsoonal influence in this region. Upper Basin precipitation is projected to increase in the fall and winter while the Lower Basin is expected to experience a decrease. Despite drying spring conditions in the Upper Basin, annual precipitation is projected to increase in the higher elevations due to higher winter precipitation increases in these regions. Projections demonstrate a bi-modal pattern of precipitation changes in fall and winter, with the Upper Basin projected to experience increases, while the Lower Basin is projected to experience decreases. The division of wetter versus drier conditions in the winter moves northward with continued warming through time consistent with an expansion of the Hadley cell and more northerly storm tracks (Seager et al., 2010).

8.3.2 Hydrologic Processes

Figures B-39 and B-40 present grid cell-based VIC model output via Basin-wide spatial plots for ET, runoff, soil moisture fraction, and SWE. For each future time period and for each parameter, the mean projected annual changes are presented. Projected seasonal changes for these parameters can be found in Appendix B7.

Figure B-39 shows the percent change in mean annual ET and mean annual runoff. Runoff is generally projected to decrease substantially (up to 30 percent) in the northeast and south central portions of the Basin. Elsewhere, projected decreases are generally within 15 percent of the historical period through 2080. Runoff is projected to increase for small areas in the northern and southwest portions of the Basin. The increases in the northern portion of the Basin are an important finding and contribute significantly to mitigate reduced runoff trends for much of the rest of the Basin.

Figure B-40 shows the mean percent change in April SWE and June 30 soil moisture fraction. With few exceptions, SWE is projected to decline by up to 30 percent throughout the Basin by 2025. Soil moisture fraction is projected to decrease by 5 to 10 percent throughout the Basin for the three future time periods. The most substantial decline occurs in the northeast portion of the Basin.

Maps of seasonal changes in ET, runoff, soil moisture, and SWE for the three future 30-year periods are included in Appendix B7 and are summarized here.

Projected 2055 changes in ET vary substantially throughout the Basin. In general, ET is projected to increase during fall and winter, but decrease during summer for the majority of the Basin. Projected ET changes exhibit considerable geographic variability and range in magnitude during spring, when portions of the Upper Basin see ET increases of up to 30 percent and portions of the Lower Basin see ET decreases of up to 30 percent. During summer, projected 2055 changes in ET range from -5 to -10 percent in most locations.

Projected 2055 changes in runoff also vary substantially throughout the Basin. In most seasons, runoff declines throughout the Basin. However, increases are projected for portions of the Upper Basin in fall and winter, and for the extreme southwestern portion of the Basin for all seasons. The projected decline in runoff is most substantial during spring, when several areas in both the Upper and Lower Basins feature a runoff reduction of up to 30 percent. Portions of the Upper Basin exhibit reduction of a similar magnitude during both summer and fall.

FIGURE B-39
Mean Projected Percent Change in Annual ET and Runoff
2025 (2011-2040) versus 1985 (1971-2000); 2055 (2041- 2070) versus 1985 (1971-2000); and 2080 (2066-2095) versus 1985 (1971-2000).

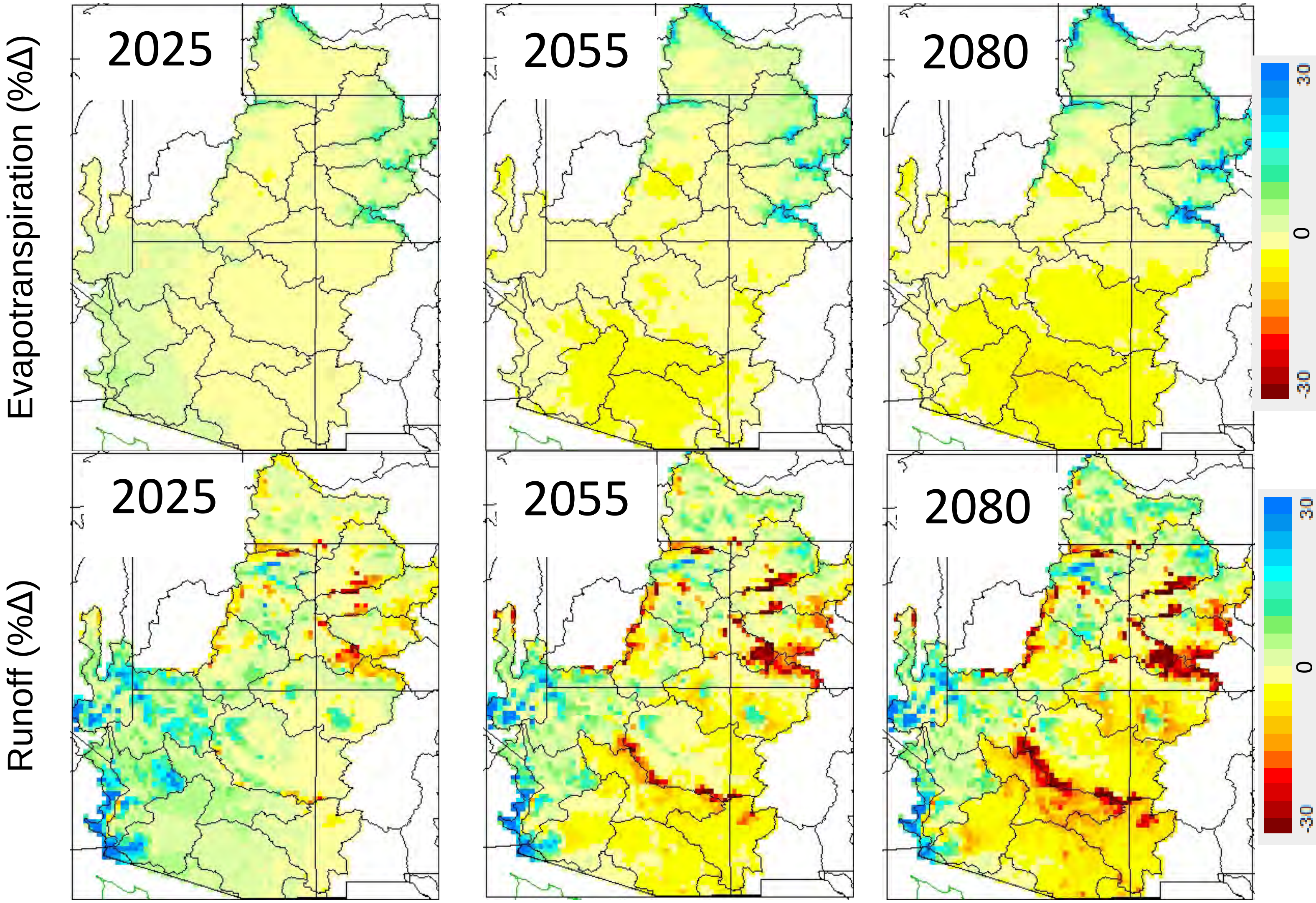
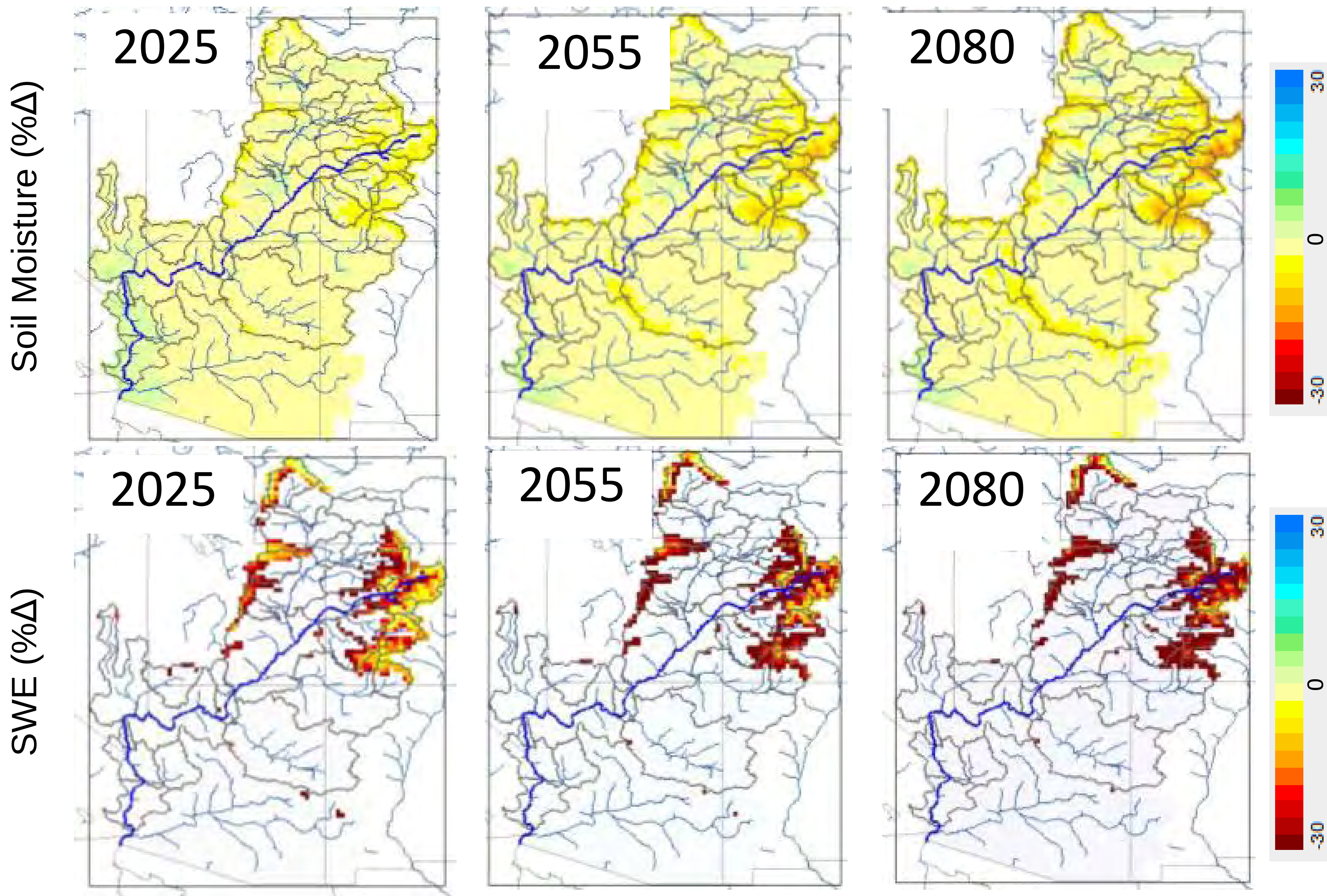


FIGURE B- 40
Mean Projected Percent Change in June 30th Soil Moisture Fraction and April SWE
2025 (2011-2040) versus 1985 (1971-2000); 2055 (2041-2070) versus 1985 (1971-2000); and 2080 (2066-2095) versus 1985 (1971-2000).



The results of the watershed-based statistical analysis of VIC model output (climatological and hydrologic parameters) are presented for two representative Basin watersheds. The selected watersheds are those immediately upstream of Colorado River at Glenwood Springs (Colorado), and Colorado River at Hoover Dam. These select watersheds represent a high elevation headwaters region in the Upper Basin and a lower elevation, warmer region in the Lower Basin. Additional locations representing a more robust cross-section of the Basin are included in Appendix B7.

Figures B-41 and B-42 each present the changes in six hydrologic parameters (precipitation, temperature, ET, runoff, SWE, and soil moisture) from the 30-year historical period (1971-2000) to three future 30-year periods: 2011-2040 (2025); 2041-2070 (2055); and 2066-2095 (2080). Figure B-41 presents these hydrologic parameter changes for the Colorado River at Glenwood Springs, Colorado. The results for this watershed are representative of those for other watersheds in the high elevation Upper Basin.

- Precipitation: In the three future time periods, the Upper Basin watersheds experience a shift in the timing of precipitation; more precipitation occurs in fall and winter (November through March) and less occurs in spring (April through June) relative to historical conditions.
- Temperature: Monthly temperatures increase from 1.0°C to 1.5°C by 2025, and by 2.5°C to 4.0°C by 2080 relative to the 30-year historical period of 1971-2000.
- ET: While ET is relatively unchanged from September to March, spring months (April through June) feature a marked increase.
- SWE: Snowpack, as indicated by SWE, is consistently less in the future than in the historical period, particularly from March through May. Shifts in both runoff and soil moisture fraction indicate that some portion of the reduction in spring SWE may be related to earlier snowmelt.
- Runoff: Runoff is projected to increase in March, April, and May while both precipitation and SWE are reduced during April and May. This suggests an earlier snowmelt that supplies the increased runoff from March through May and contributes to a reduction in snowpack. This is further supported as runoff is substantially reduced in June and July, suggesting that the melting snowpack, which historically supplied runoff during these months, has been depleted by this time.
- Soil moisture: Similarly, soil moisture fraction is increased from February through April in conjunction with increased snowmelt infiltration. However, relative to historical conditions, the projected soil moisture fraction is lower for the remainder of the year, exhibiting the most substantial reduction in June.

Figure B-42 presents these plots for the Colorado River at Hoover Dam. The results for this watershed are representative of those for other watersheds in the Lower Basin. Due to the limited presence of snowpack and its limited role in the hydrologic processes of this region, SWE results are not included. Relative to the Upper Basin, the changes projected for the Lower Basin are smaller in magnitude on an absolute scale (e.g., change in millimeters rather than change in percentage).

- Precipitation: In the Lower Basin, precipitation is projected to decrease during half of the year, with spring exhibiting the most notable decline.
- Temperature: Monthly temperature increases are projected throughout the year ranging from 1.5°C by 2025 to 4.0°C by 2080.
- Evapotranspiration: ET is noticeably reduced in late spring and early summer, though modest increases are projected for winter. The marked reductions in late spring and early summer are likely due to the reductions in precipitation, runoff, and soil moisture that occur during these times.
- Runoff: Runoff increases during the winter and decreases by about the same amount during the spring. In 2080 a net increase in runoff is projected. This result is currently under investigation and may be due to the temporal (monthly to daily) disaggregation method applied to the GCM projections.
- Soil Moisture: Soil moisture fraction is projected to be lower year round, with the largest reductions occurring in the spring.

In the future, the Lower Basin is generally projected to have less water in the form of precipitation and soil moisture year round, and especially during winter and spring. However, the magnitude of these reductions is modest.

FIGURE B-41
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
01-Colorado River at Glenwood Springs, Colorado (Upper Basin).

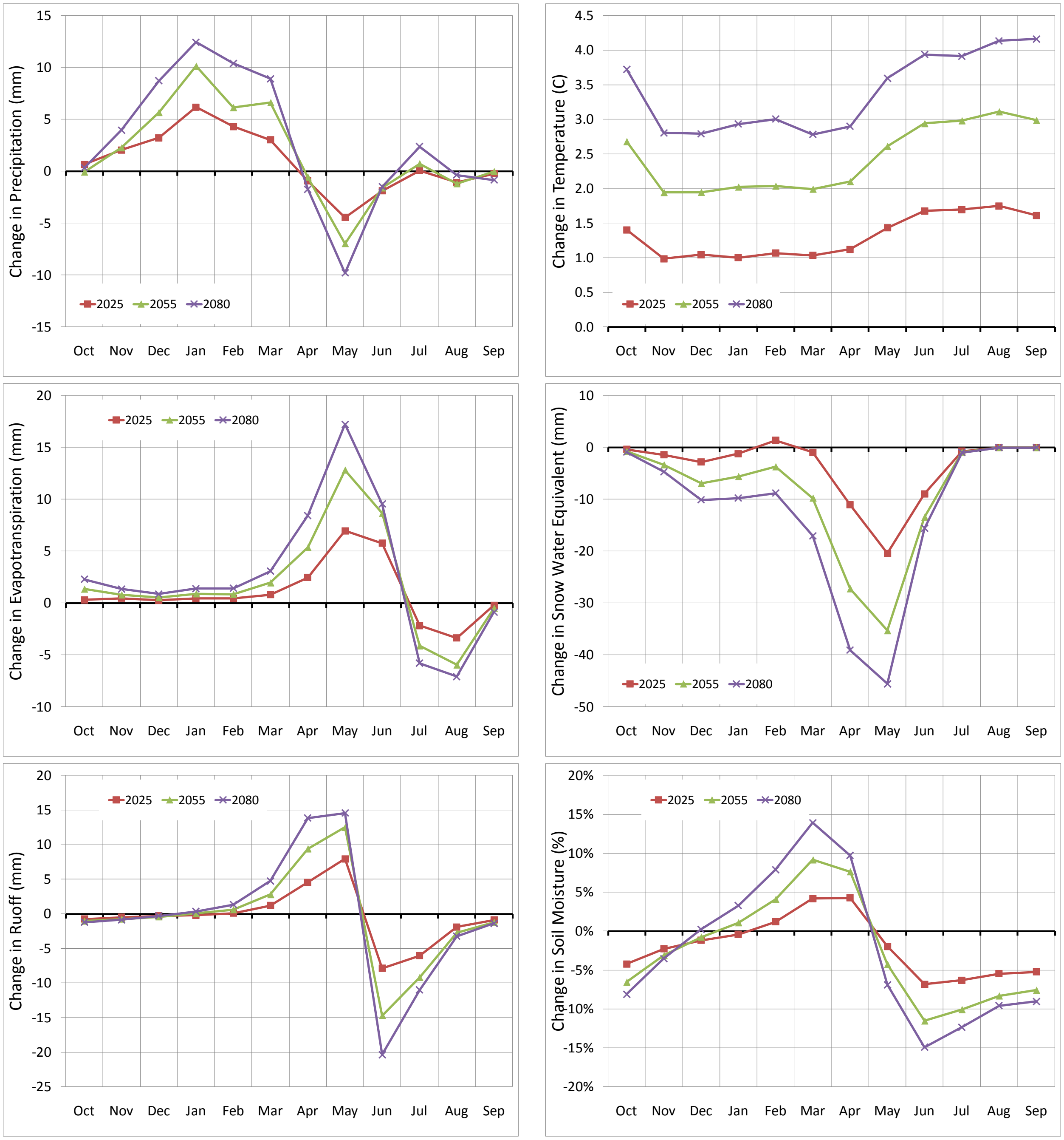
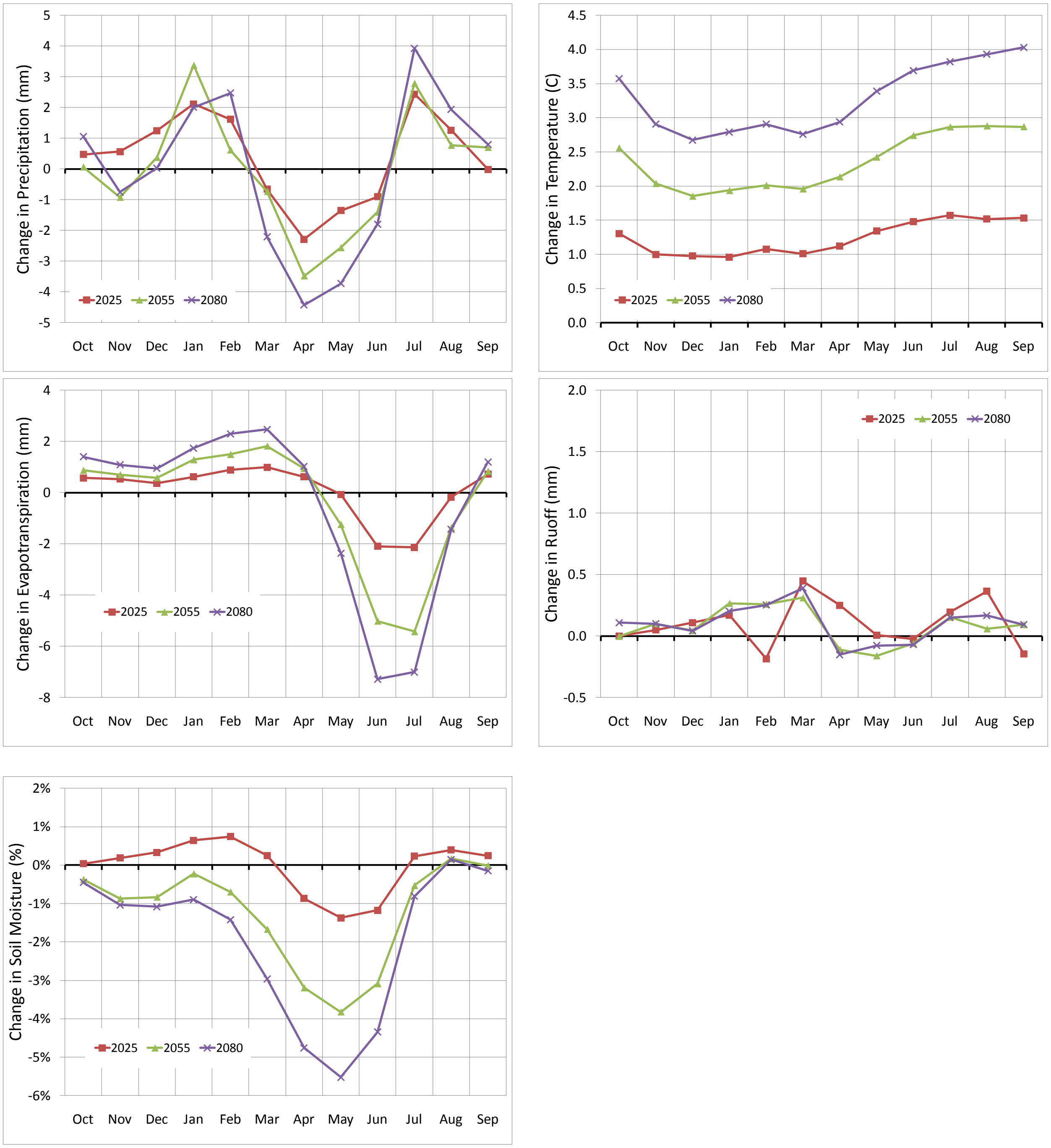


FIGURE B-42
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
25-Colorado River at Hoover Dam.



Summary of Changes in Hydrologic Processes

- Evapotranspiration is projected to increase across the Basin during seasons of highest available soil moisture. Increases are projected in the Upper Basin (at lower elevations) and the Lower Basin in fall and winter as snowpack is not significant and warmer temperatures exist. Substantial decreases in the Upper and Lower Basin are projected in summer as soil moisture is depleted earlier than under historical conditions. During spring, peak increases in ET are projected in the Upper Basin (at higher elevations) as higher winter precipitation and earlier snowmelt allow a higher percentage of potential ET to be satisfied. Conversely, in the Lower Basin, the largest decreases are projected during the spring as precipitation, runoff, and soil moisture are reduced during this time. ET changes described here are from natural watershed and non-irrigated areas. ET effects on irrigated areas and water demand is discussed *Technical Report C – Water Demand Assessment*.

- Snowpack is projected to decrease as more precipitation falls as rain rather than snow and warmer temperatures cause an earlier melt. Decreases of snowpack in the fall and early winter are expected in areas where precipitation is not changed or is increased, and is caused by a greater liquid form of precipitation due to warming. Substantial decreases in spring snowpack are expected and projected to be widespread, due to earlier melt or sublimation of snowpack.

- Soil moisture represents a significant portion of the seasonal watershed storage and buffers monthly changes in water availability and consumptive use. The interplay among precipitation, snowpack, ET, and runoff causes changes in soil moisture conditions. In general, soil moisture is depleted earlier in the year and deficits persist longer into the late fall and early winter as compared to historical conditions. In regions with overlying snowpack, earlier melt implies earlier contribution to soil moisture storage and an earlier opportunity for ET to consumptively use this stored water. In all regions, there is projected to be increased potential ET due to warming. However, actual ET is governed by water availability and when such soil moisture storage is depleted actual ET is curtailed. Reductions in soil moisture at the beginning of summer (approximated as June 30th) are modest but consistent throughout the Basin. Larger reductions are projected in the higher elevation portions of the Basin where moisture persists longer. Overall, the watershed enters the winter season with larger soil moisture deficits and greater opportunity to store and consume winter precipitation.

- Runoff (both direct and baseflow), the balance of hydrologic processes affecting the supply and demand at the local grid-scale, is spatially diverse, but is generally projected to decrease except in the northern Rockies and the extreme western portion of the Lower Basin. As with precipitation, runoff is projected to increase significantly in the higher elevation Upper Basin during winter, but exhibits decreases during spring and summer. Increases in precipitation in the summer across the southwestern portion of the Basin are consistent with higher precipitation rates possibly associated with a more active monsoon. However, runoff increases in this region in other seasons are associated with more intense storm events, despite decreases in total seasonal precipitation. At this time, it is uncertain whether such increases in storm intensity are to be expected or whether this is an artifact of the temporal (monthly to daily) disaggregation of the GCM projections.

Work is ongoing to better understand this issue. Basin-wide runoff efficiencies decrease by mid century by up to 7 percent, suggesting that the hydrologic response to warming pushes toward greater loss of runoff, even in the absence of any signification changes in precipitation.

8.3.3 Climate Teleconnections

Climate change projections of ENSO characteristics for the balance of this century are model dependent and inconclusive. The current state of GCMs does not consistently capture the dynamics of ENSO and other longer-term indices. Yeh and Kirtman, 2007, investigated two coupled GCMs—the Meteorological Research Institute, and Geophysical Fluid Dynamics Laboratory models—to analyze projected ENSO amplitude changes using a four times carbon dioxide emission scenario. They determined that despite the large changes in the tropical Pacific mean state, the changes in ENSO amplitude are highly model dependent. Results suggest that the understanding of changes in ENSO statistics among various climate change projections is highly dependent on whether the model ENSO is in the linear or nonlinear regime. ENSO and PDO are of only limited skill in determining basin precipitation; thus, even improved simulation results of these indices may be of limited value in making assessments of future supply conditions. Further research is needed to investigate the teleconnections and the direction of these teleconnections in the future.

8.3.4 Streamflow

Natural streamflows were simulated at the 29 flow locations for each of the 112 climate projections. Figure B-43 displays all of the individual 112 sequences in the Downscaled GCM Projected scenario. The sequence bolded in Figure B-43 also appears in Figure B-44, which is a statistical summary of the 112 sequences. In Figure B-44, the mean annual flow of the 112 sequences at this location declines substantially over time due to changes in hydrologic processes. Mean annual flows at Lees Ferry for the 50-year period of the Study (2011-2060) are approximately 13.6 maf. This represents a reduction in streamflow of approximately 7 percent compared to the period 1950-1999 (14.6 maf), or approximately 9 percent when compared to the long-term period 1906-2007 (15.0 maf). Appendix B6 shows a similar set of results for Green River at Green River, Utah; Colorado River at Cisco; San Juan near Bluff; and Colorado River above Imperial Dam. At each of these locations, flows are projected to decrease. The simulated future range of streamflows within the 10^{th} – 90^{th} percentile is similar to the range in the observed record. However, a few projections (less than 10 percent) show considerably more annual variability than the observed. While simulated future minimum flows are similar to those in the observed record, the maximum annual flows are significantly higher. Presumably these flows are from very wet climate projections and it is unknown whether these projections reflect an overly-sensitive response to warming even in the next decade. This is an area of ongoing research and will be addressed in Interim Report No. 2.

FIGURE B-43
Colorado River at Lees Ferry Natural Flow for 112 Sequences for the Downscaled GCM Projected Scenario

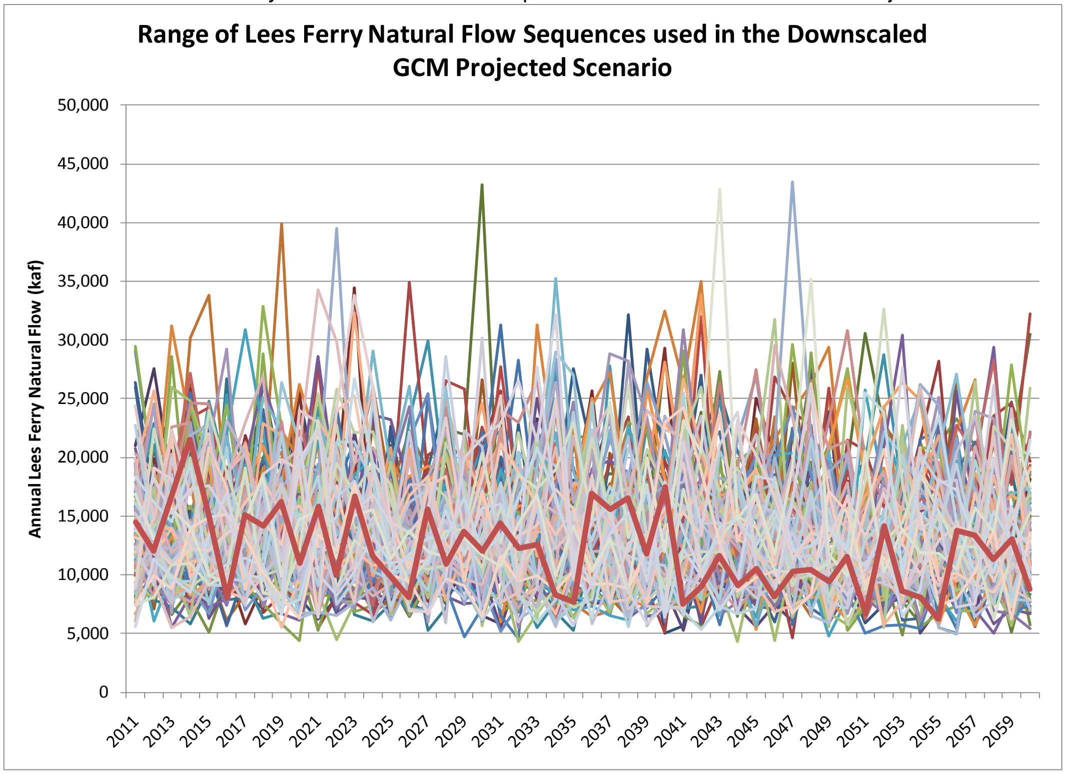


FIGURE B-44
Colorado River at Lees Ferry Natural Flow Statistics for the Downscaled GCM Projected Scenario
Median (line), 25th – 75th percentile band (dark shading), 10th – 90th percentile band (light shading), max/min (whiskers), selected individual realization (red line), and 1906-2007 observed mean, min, and max (dashed lines).

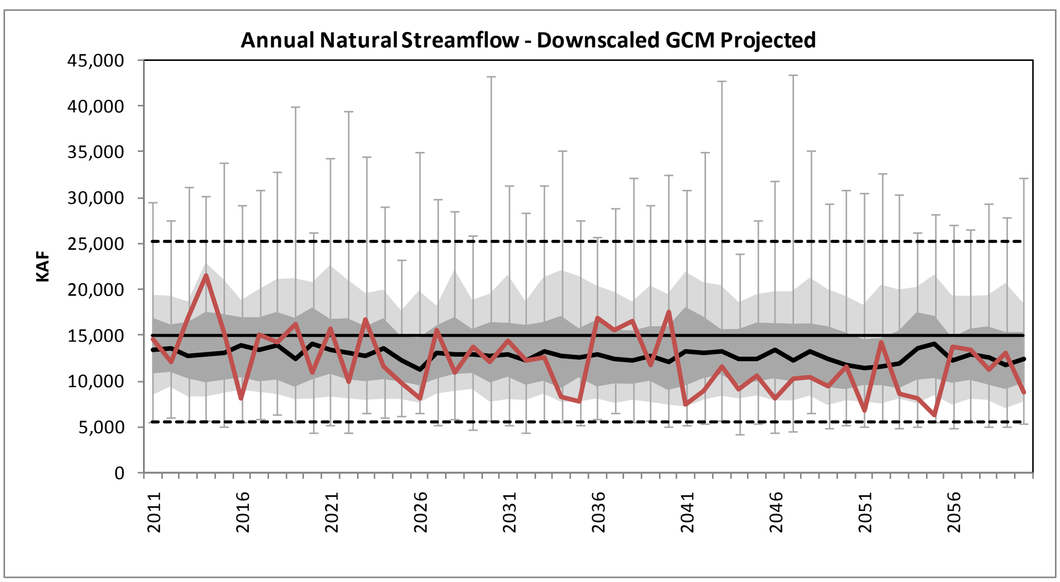
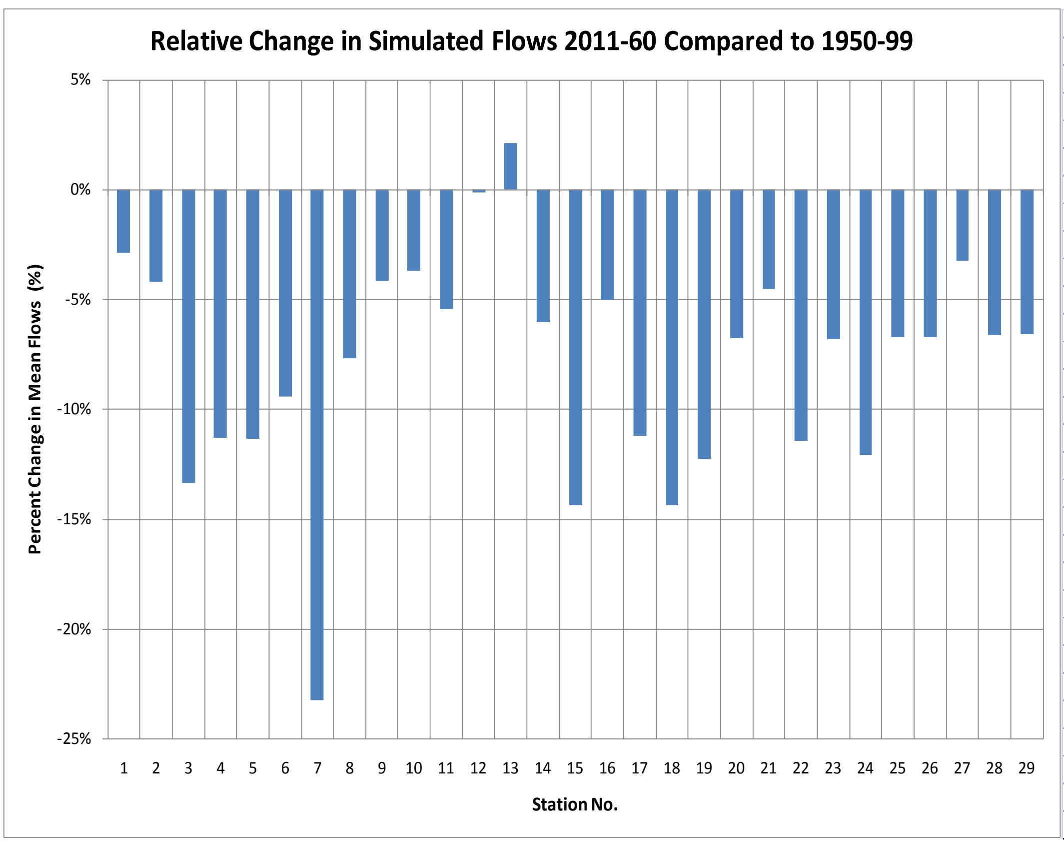


Figure B-45 shows the mean annual percent change for all 29 locations from 2011-2060 as compared to the 50-year historical period of 1950-99. The comparison here is not made to the observed 1906-2007 period, but rather to the historical VIC-simulated period because the same biases are inherent in both the future and historical VIC-simulated periods. By comparing these two simulated periods, a truer indication of the percent change is obtained.

All locations except the Little Snake River, are projected to experience decreasing annual flows. The Dolores River, White River, and San Juan River are projected to experience the largest percentage decrease in annual flows (greater than 10 percent). The Green River and upper watershed of the Colorado River are projected to experience smaller reductions in streamflow (less than 5 percent). These spatial differences in streamflow changes appear to be largely related to the location of the watershed in relation to the precipitation pattern changes (more northerly) and the relative elevation differences among watersheds (higher elevation). In general, smaller sub-basins that are further north and at higher elevations (such as the Yampa River and Little Snake River) may be expected to have increasing flows. given projected increases in precipitation. Although precipitation is projected to increase in some larger sub-basins at lower elevations (such as the Green River), a decrease in flow is projected, possibly a result of the dominant role of increased temperature in these regions.

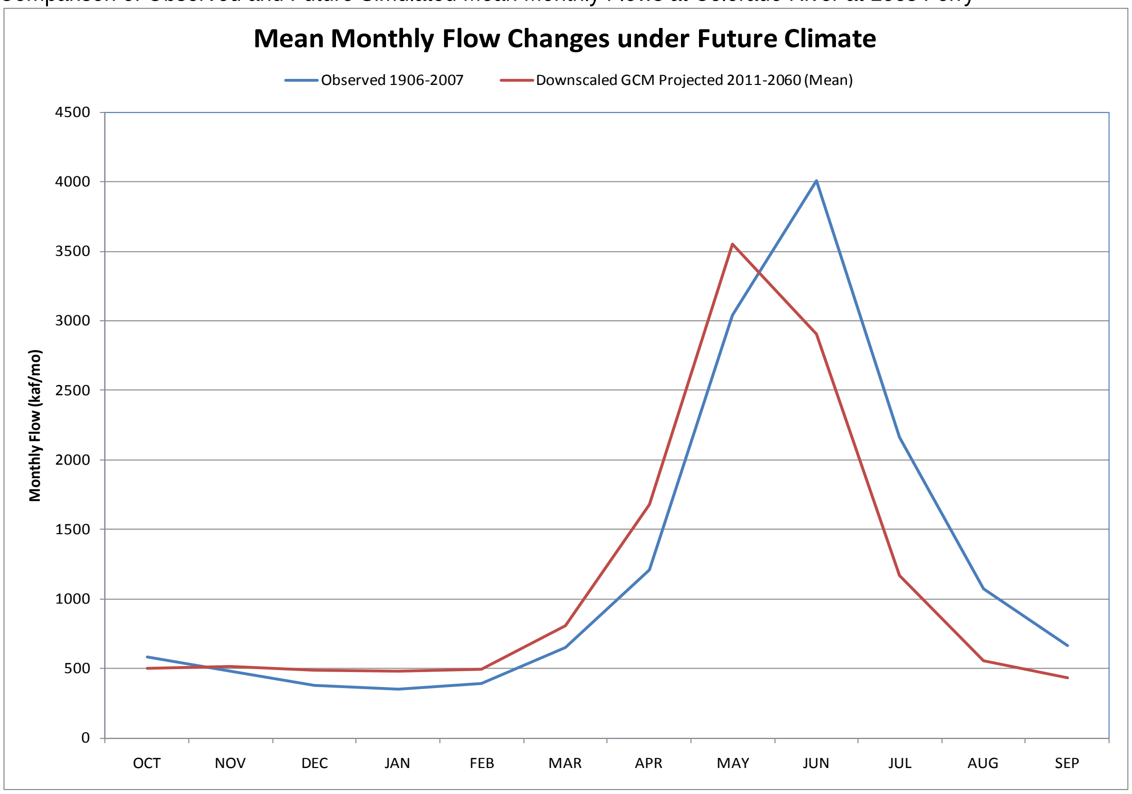
FIGURE B-45
Simulated Relative Change in Mean Annual Flows (Ensemble Mean) by 2011-2060, as Compared to1950-1999 for each of the 29 Natural Flow Locations.



No.	Location
1	Colorado River at Glenwood Springs, CO
2	Colorado River near Cameo, CO
3	Taylor River below Taylor Park Reservoir, CO
4	Gunnision River above Blue Mesa Reservoir, CO
5	Gunnison River at Crystal Reservoir, CO
6	Gunnison River near Grand Junction, CO
7	Dolores River near Cisco, UT
8	Colorado River near Cisco, UT
9	Green River below Fontenelle Reseservoir, WY
10	Green River near Green River, WY
11	Green River near Greendale, UT
12	Yampa River near Maybell, CO
13	Little Snake River near Lily, CO
14	Duchesne River near Randlett, UT
15	White River near Watson, UT
16	Green River at Green River, UT
17	San Rafael River near Green River, UT
18	San Juan River near Archuleta, NM
19	San Juan River near Bluff, UT
20	Colorado River at Lees Ferry, AZ
21	Paria River at Lees Ferry, AZ
22	Little Colorado River near Cameron, AZ
23	Colorado River near Grand Canyon, AZ
24	Virgin River at Littlefield, AZ
25	Colorado River below Hoover Dam, AZ-NV
26	Colorado River below Davis Dam, AZ-NV
27	Bill Williams River below Alamo Dam, AZ
28	Colorado River below Parker Dam, AZ-CA
29	Colorado River above Imperial Dam, AZ

While annual flows show decreases and likely some expansion in variability, monthly flows exhibit a significant shift in timing. Figure B-46 shows the simulated mean monthly flows from the climate projections for the Colorado River at Lees Ferry compared to the observed monthly flows. Commensurate with the seasonal changes in temperature, precipitation, and hydrologic processes, the peak streamflow occurs about one month earlier (from June to May) and is approximately 500 thousand acre-feet (kaf) lower. In addition, slight increases in winter streamflow and substantial reductions occur in spring and summer. The wintertime increases are likely associated with increased precipitation in the Upper Basin, while spring and summer decreases are likely associated with earlier melt of the snowpack and reduced precipitation patterns.

FIGURE B-46
Comparison of Observed and Future Simulated Mean Monthly Flows at Colorado River at Lees Ferry



The inter-annual variability in streamflow is another important component of water supply. Deficit statistics using the identical methods as those described for the historical supply were computed for each of the 112 climate projections. The 1906-2007 observed mean of 15.0 maf was used to set the threshold for determining whether the system was in a deficit or surplus. For the purpose of this report, “deficit” is defined as a consecutive 2-year period when the mean is less than the observed long-term mean of 15.0 maf. Similarly, “surplus” is defined as a consecutive 2-year period when the mean is above 15.0 maf.

Figure B-47 illustrates the frequency and magnitude of both deficit and surplus spells. The inset figure shows the frequency occurrence of a specific spell length across all projections. The median exceedance probability of a surplus spell longer than 0 years is 30 percent, indicating that, when as measured against the 1906-2007 mean annual flow of 15 maf, about a third of the years in the future would be considered to not be a deficit. In addition, deficit length may extend greater than 20 years (indicated by the 90th percentile deficit length), as compared to the current 11-year deficit. Under the Downscaled GCM Projected scenario (at the ensemble median) an 11-year deficit may occur up to 20 percent of the time and result in a cumulative deficit of 35-60 maf. The current 11-year deficit is estimated to have a cumulative deficit of approximately 35 maf. The results also suggest that under some climate projections sustained periods of dryness will occur (deficit lengths greater than 50 years). However, most projections result in long-term mean annual flows that are less than the 15 maf observed mean. The future climate essentially arrives at a new mean state. Thus deficits may need to be evaluated against the projection-specific, long-term mean to reflect this new inter-annual variability about the new mean.

Figure B-48 is identical to Figure B-47 except that the threshold for deficit and surplus is determined from the projection-specific, long-term mean, rather than the observed mean. The drought depiction is considerably different under these conditions. As expected, deficit and surplus frequencies are roughly equal. In addition, deficit spell lengths do not exceed 17 years and are a maximum of 8 years at the median of the projections. Deficit magnitudes at the 11-year deficit remain in the 35-60 maf range. Under this perspective, the inter-annual variability is not substantially different than the recent observed period, but rather the Downscaled GCM Projected means are significantly reduced, leading to the perspective of relatively sustained deficit when measured against recent observed flows. There is no absolute correct perspective; thus, both methods are presented here.

FIGURE B-47
Simulated Deficit and Surplus Spell Length and Magnitude for All 112 Climate Projections (Threshold Defined As 1906-2007 Mean Annual Flow ~ 15 maf)
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).

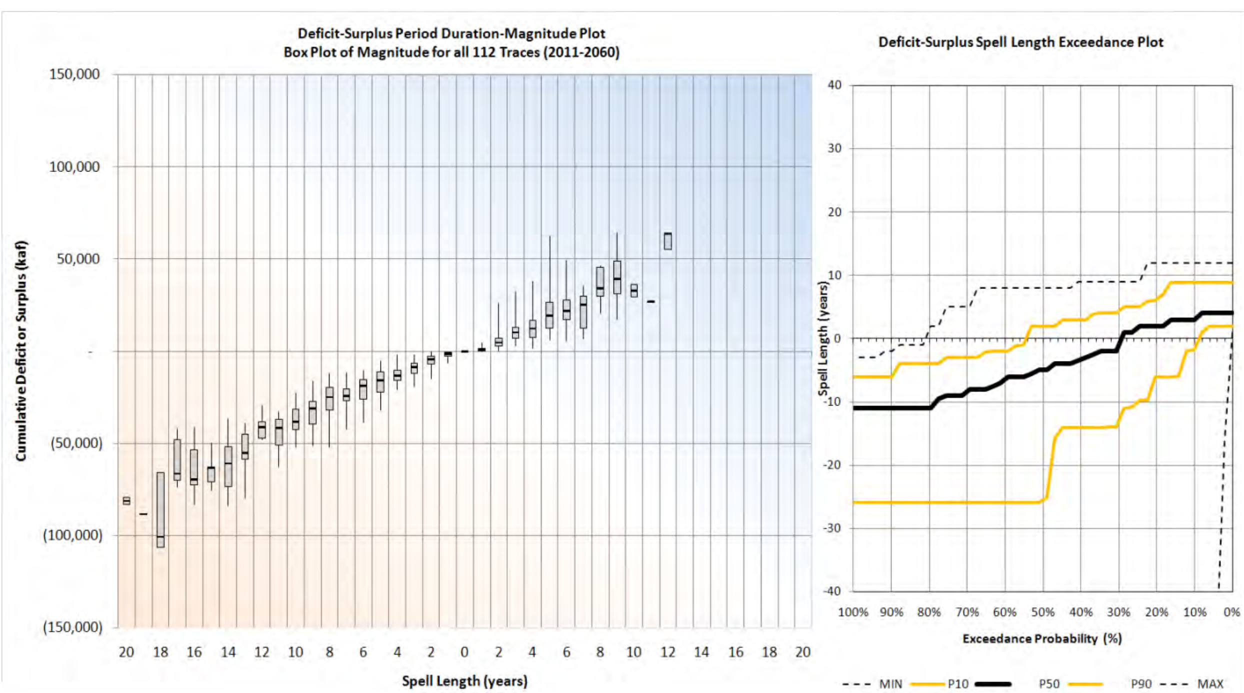
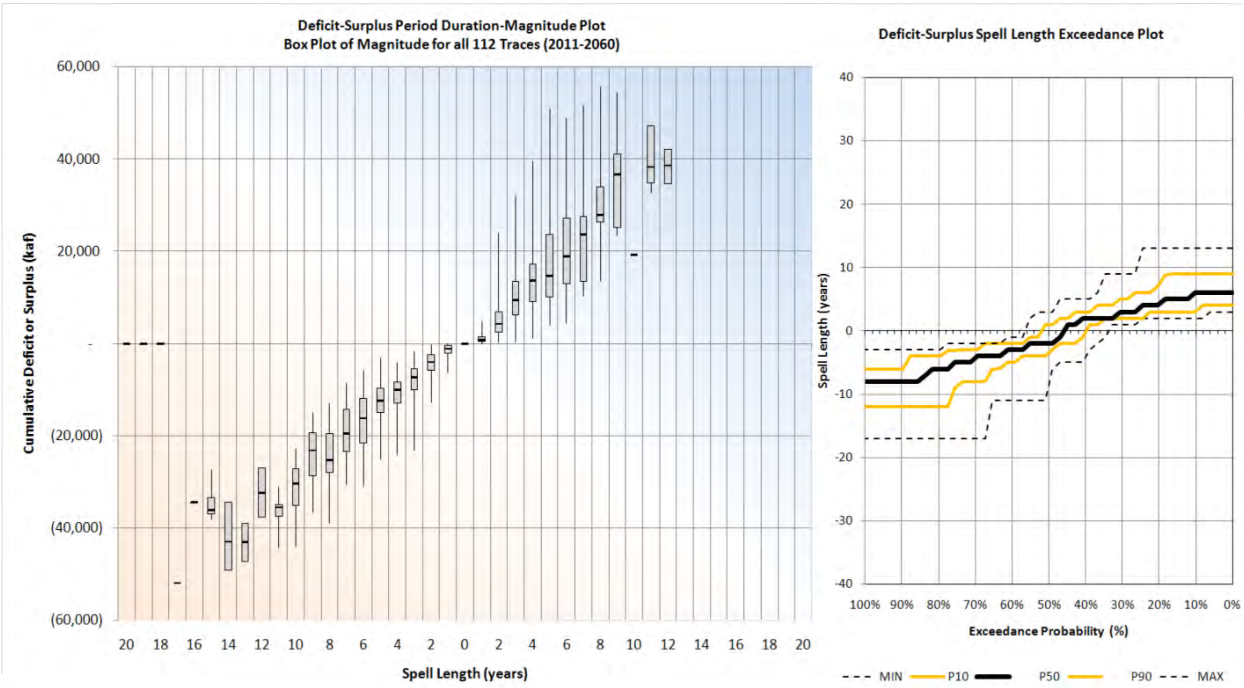


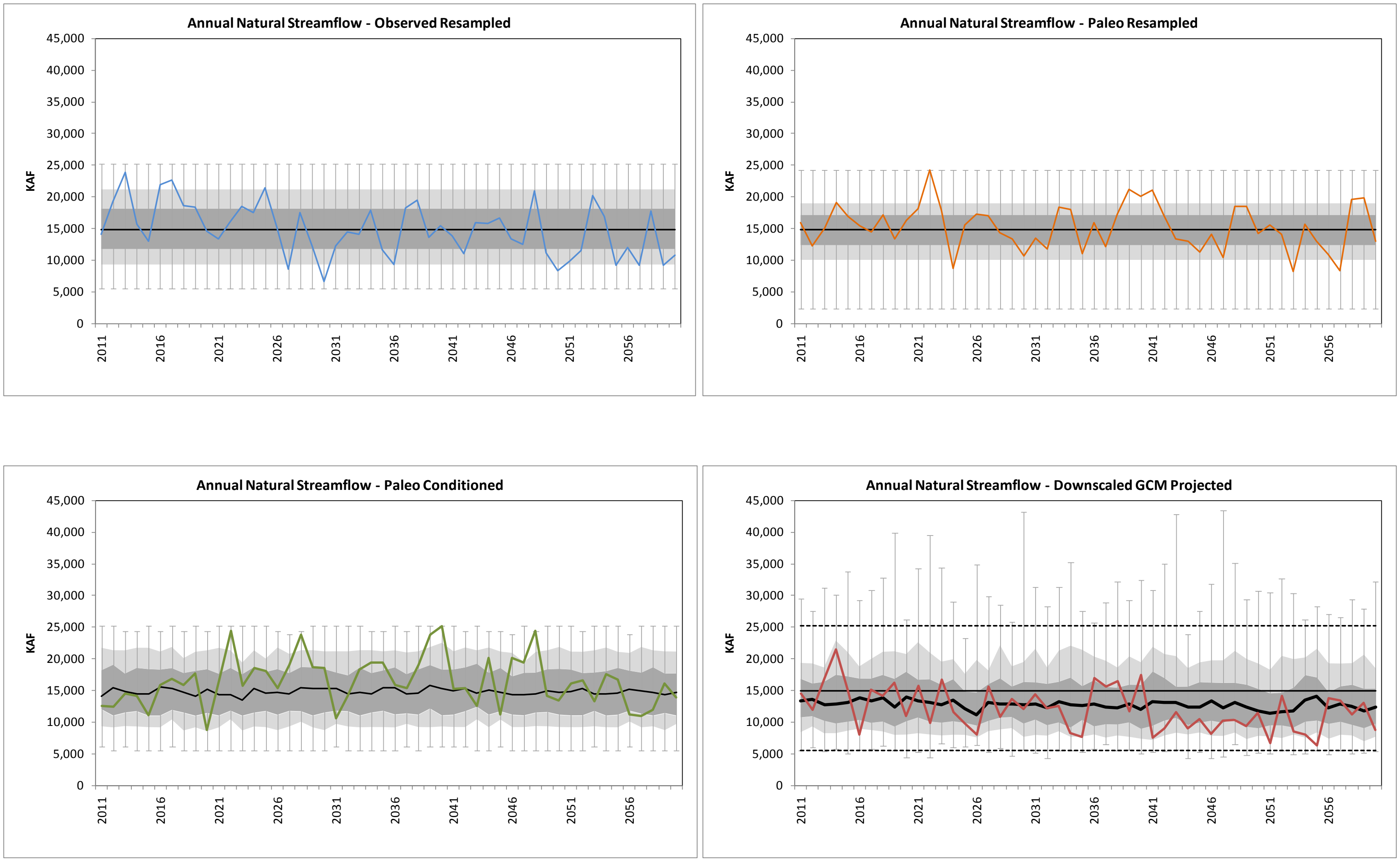
FIGURE B-48
Simulated Deficit and Surplus Spell Length and Magnitude for all 112 Climate Projections (Threshold Defined as Individual Projection Mean for 2011-2060)
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



9.0 Comparison of Future Supply Scenarios

The Water Supply Assessment described in this report includes four distinct supply scenarios that attempt to bracket the range of conditions that might be experienced over the course of the next 50 years. The scenarios include direct use of the observed record (Observed Resampled scenario), direct use of the paleo reconstructions (Paleo Resampled scenario), blends of observed and paleo sequences (Paleo Conditioned scenario), and use of future climate projections and hydrologic modeling (Downscaled GCM Projected scenario). Figure B-49 shows the range of annual flows for the Colorado River at Lees Ferry for each of the scenarios in a four-panel series.

FIGURE B-49
Annual Colorado River at Lees Ferry Natural Flow Time Series for Supply Scenarios (median in bold black line, inter-quartile range in dark shading, 10th – 90th percentile range in light shading, selected individual sequence in bold colored line, and max/min as whiskers). For the Downscaled GCM Projected Scenario, max/min of Observed Record in dashed line.



The Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios all have similar mean annual flows and a similar range of annual variability. The Paleo Resampled scenario contains individual years of flows lower than Observed Resampled, but a narrower band of variability within the inter-quartile range. The Paleo Conditioned scenario, by design, includes a similar range of annual flows as the Observed Resampled. The Downscaled GCM Projected scenario reflects possible changes in climate beyond what occurred historically and has lower mean annual flows, while expanding the annual variability range through increased maximum annual flows. Mean annual natural flows for the Colorado River at Lees Ferry range from 14.7-15.0 maf for the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios. The Downscaled GCM Projected scenario results in mean annual flows of approximately 13.6 maf.

Since each supply scenario includes multiple realizations there is a range associated with the flow statistics. Figure B-50 graphically depicts these annual flow statistics. The range of mean flows is greatest under the Downscaled GCM Projected scenario with the inter-quartile range spanning roughly 12.5-15 maf and the absolute range covering 10-17 maf. Especially with respect to the use of climate projections, the ensemble mean or median should be considered more useful than any individual projections. This ensemble mean or median has been shown to perform better than any individual projection against a range of historical climate metrics and variability and trend significance, largely due to the cancelling out of natural internal GCM model variability and cancelling out of individual model errors (see Gleckler et al., 2008 and Pierce et al., 2009 for a more complete discussion of this topic). The Paleo Resampled scenario, despite the large absolute range, has a smaller standard deviation than the other scenarios due to the tightness of the bulk of the realizations. Skew is a measure of the shape of the annual flow distribution. A skew of zero implies a perfectly “normal” distribution in which wetter years and magnitudes are evenly balanced with drier years. Most scenarios have a positive skew, suggesting a bias to the drier side of the distribution. This is particularly noticeable in the Downscaled GCM Projected scenario. The Paleo Resampled scenario has the highest year-to-year correlation as measured by the backward lag-1 correlation. This high degree of correlation is due in part to the methodology used to develop the reconstructions. The minimum annual flows are fairly consistent across the scenarios, with the Paleo Resampled scenario exhibiting the most extreme low flow condition. The Downscaled GCM Projected scenario exhibits a range of maximum annual flows well beyond those seen in any of the other scenarios.

FIGURE B-50
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for Supply Scenarios (for 2011-2060)
Figure shows the median (dash), 25th – 75th percentile band (box), and max/min (whiskers).

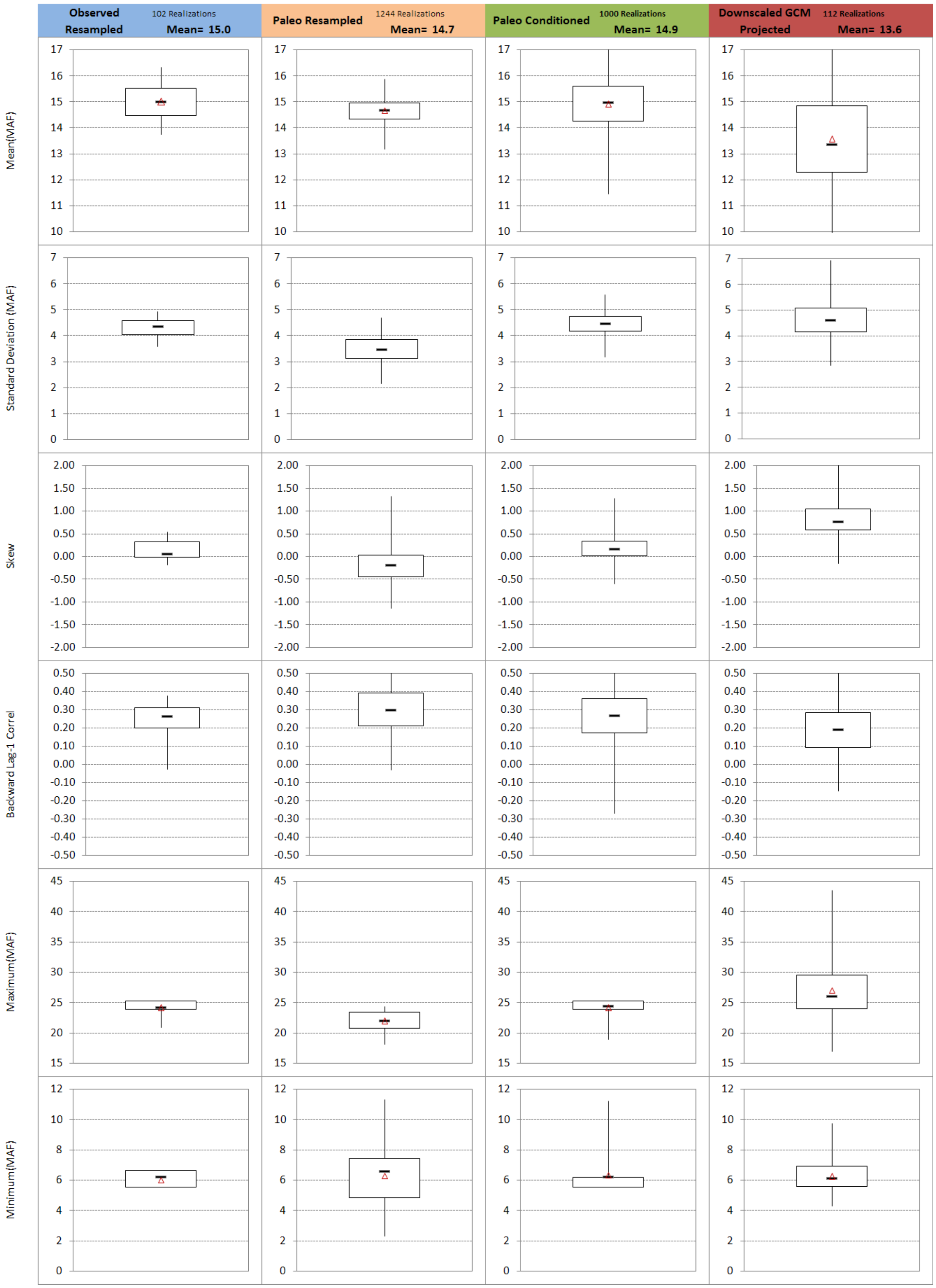


Figure B-51 provides a side-by-side comparison of each of the scenarios over the study horizon and the monthly flow range. Again, the Downscaled GCM Projected scenario demonstrates both higher high flows and lower low flows, as measured as a 5-year average. This range, combined with the reduced mean annual natural flows in this scenario, makes the Downscaled GCM Projected scenario likely the most challenging supply conditions within which to manage the Basin. The figure also shows that the monthly variability of the Downscaled GCM Projected scenario is significantly larger than any other scenario. This is particularly true in the winter and spring when the Upper Basin hydrologic processes are most active and subject to change under climate warming. The shift in peak flow timing from June to May is readily apparent in Figure B-52.

FIGURE B-51
Annual Colorado River at Lees Ferry 5-Year Natural Flow Timeseries (top) and Monthly Variability across Supply Scenarios (for 2011-2060)
Figure shows the median (dash), 25th – 75th percentile band (box), and max/min (whiskers).

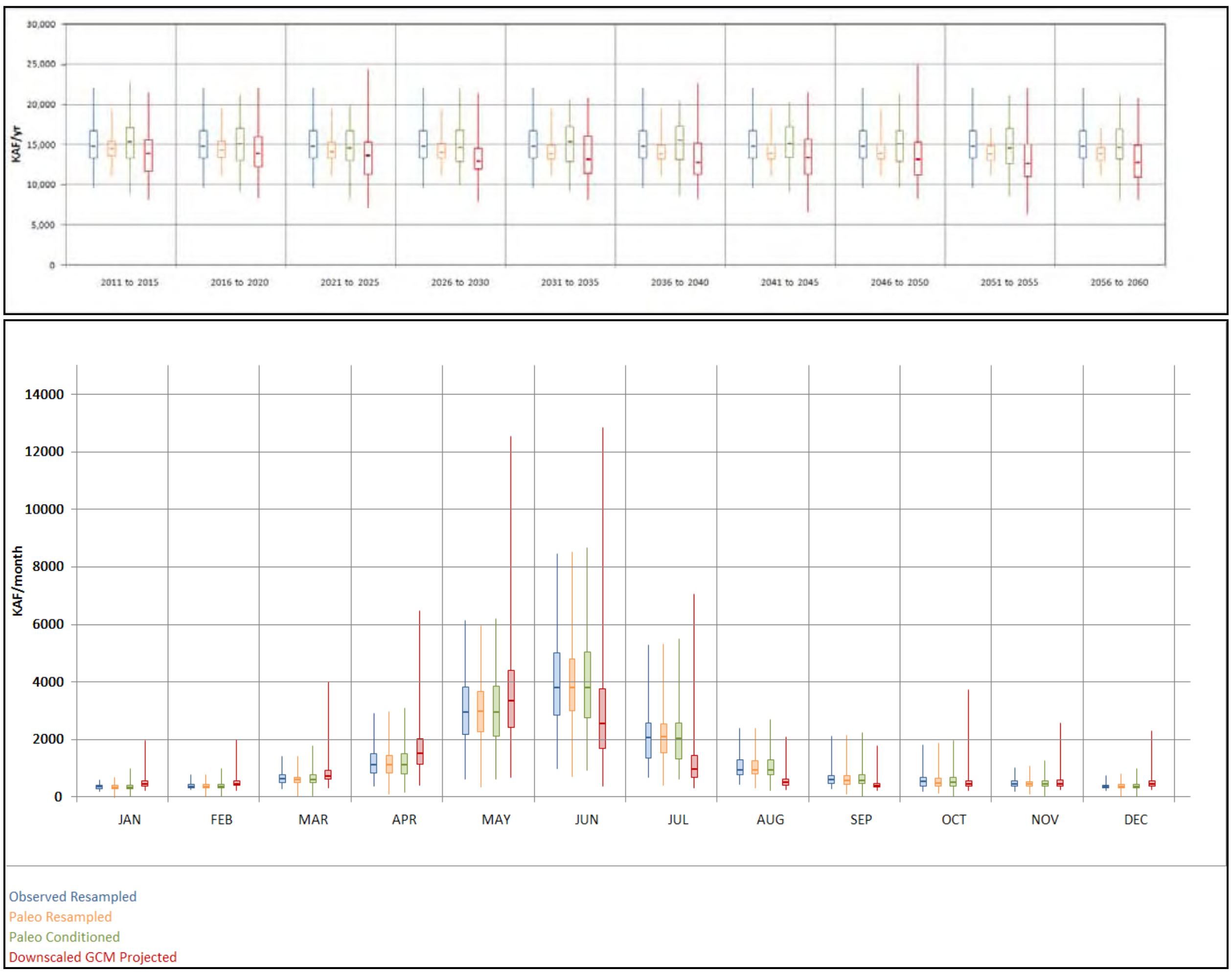
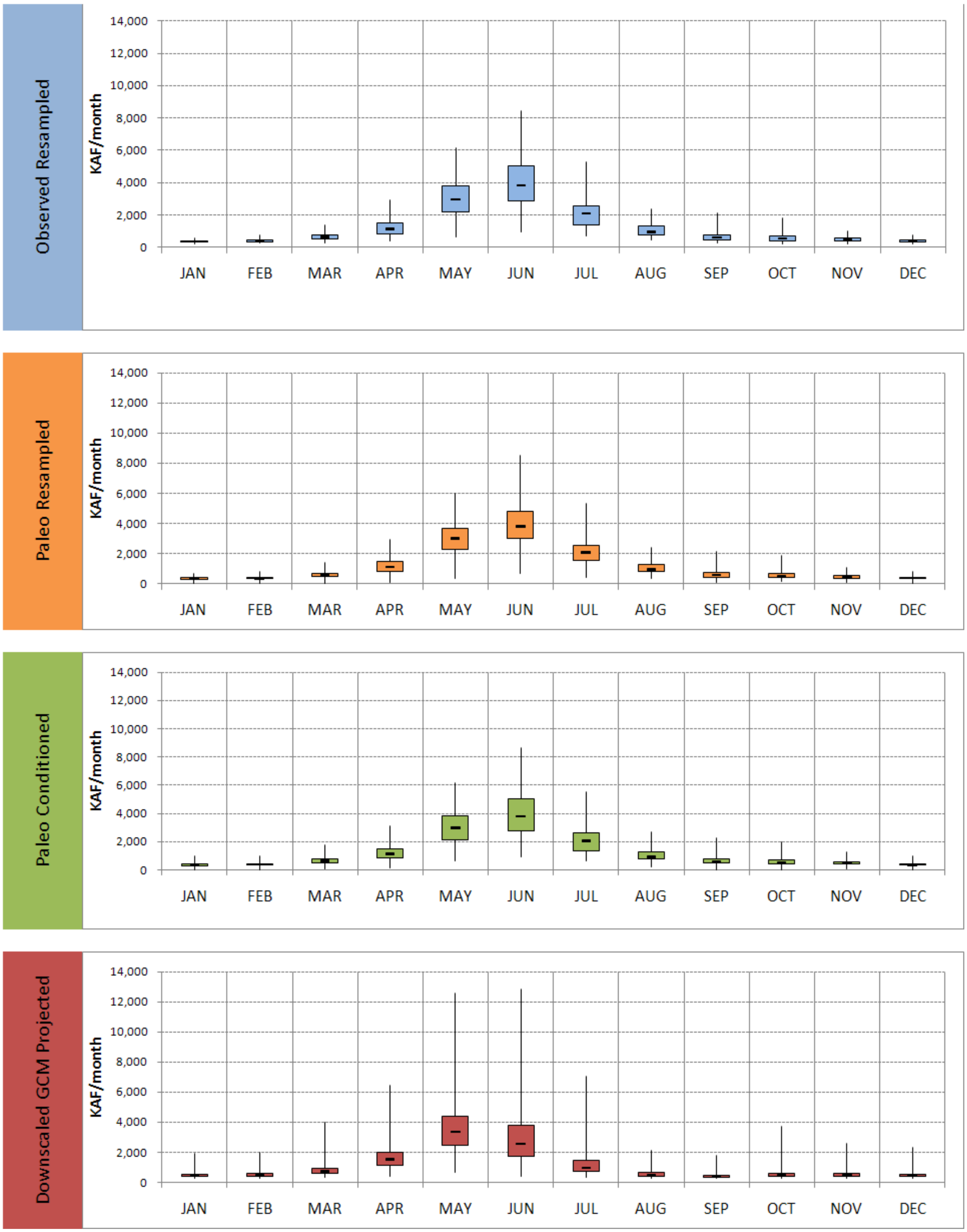


FIGURE B-52
Monthly Colorado River at Lees Ferry Natural Flow Variability for Supply Scenarios (for 2011-2060)
Figure shows the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).



The inter-annual variability of streamflow across the scenarios is characterized by determining the frequency, duration, and magnitude of deficit and surplus periods. Figure B-53 is a four-panel figure showing the length and magnitude of such spells. For example, the maximum length of sustained deficit through 2007 in the Observed Resampled scenario was 8 years (note that this length would be 11 years if the observed record extended through 2010), while the maximum sustained surplus is for 7 years. However, the Paleo Resampled, Paleo Conditioned, and Downscaled GCM Projected scenarios all produce deficit periods of 15 years in length or longer. The maximum deficit accumulated is approximately 60 maf over the 15 years of deficit (both Paleo Conditioned and Downscaled GCM Projected scenarios). However, the reduced mean annual flow in the Downscaled GCM Projected scenario causes many of the realizations to be in a sustained deficit using the recent observed flows as the measure.

Table B-1 provides a summary of the key statistics for each water supply scenario and generally provides a tabular presentation of the information presented in the figures in this section.

FIGURE B-53
Frequency, Duration, and Magnitude of Deficit and Surplus Periods for Supply Scenarios (for 2011-2060). Top figures (left to right) are the Observed Resampled and Paleo Resampled scenarios. Bottom figures (left to right) are the Paleo Conditioned and Downscaled GCM Projected scenarios.
Box plots show the median (dash), 25th – 75th percentile band (shading), and max/min (whiskers).

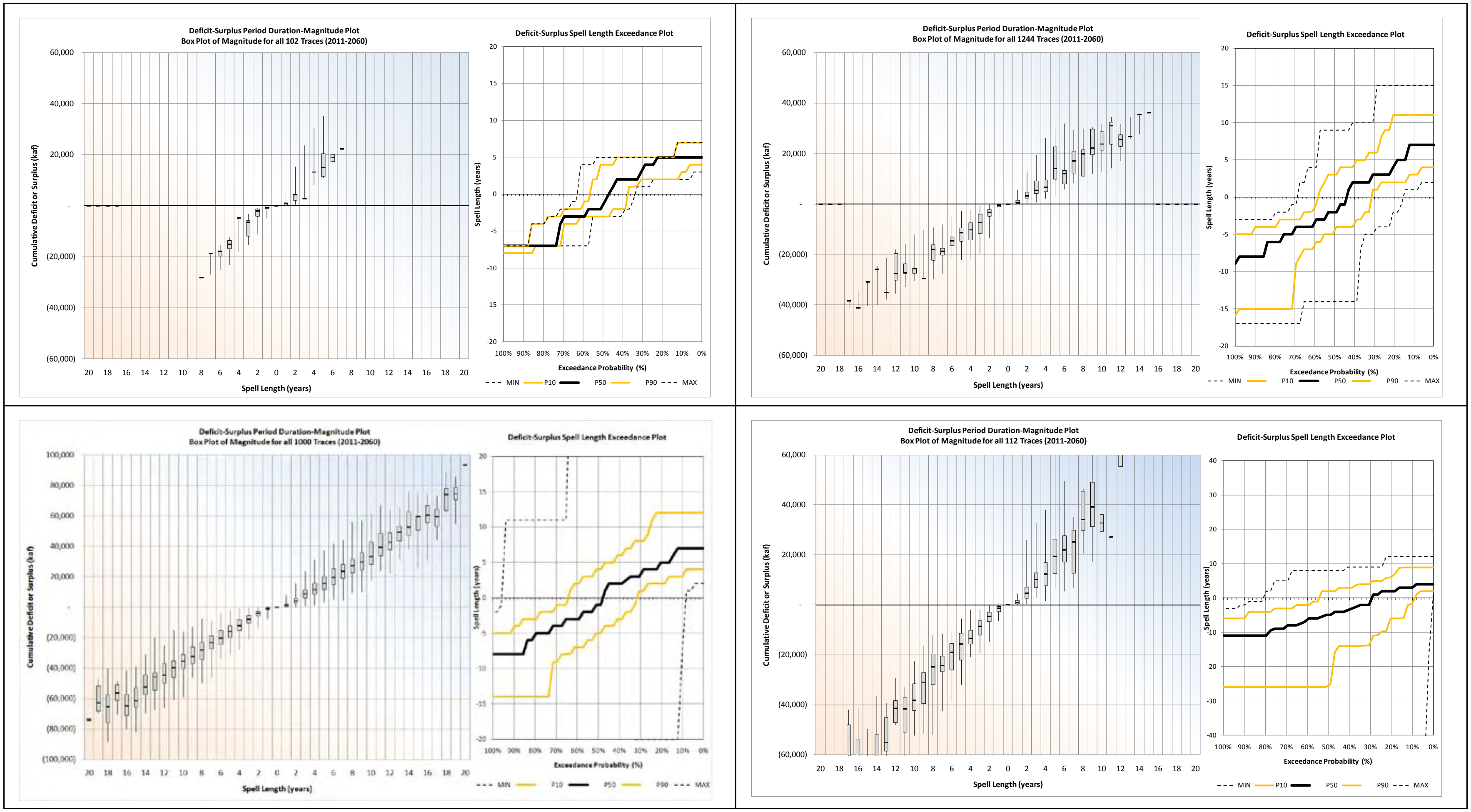


TABLE B-1
Summary of Key Streamflow Statistics for Each Water Supply Scenario for the Period 2011-2060

		Scenario			
	Statistic	**Observed Resampled**	**Paleo Resampled**	**Paleo Conditioned**	**Downscaled GCM Projected**
Annual (Water Year)	Average Annual Flow (maf)	15.0	14.7	14.9	13.6
	Percent Change from Long-Term Mean (1906-2007)	0%	-2%	-1%	-9%
	Median (maf)	15.0	14.7	15.0	13.3
	25^{th} Percentile (maf)	14.5	14.3	14.2	12.3
	75^{th} Percentile (maf)	15.5	15.0	15.6	14.8
	Minimum Year Flow (maf)	5.6	2.3	5.6	4.3
	Maximum Year Flow (maf)	25.2	24.3	25.2	43.5
Monthly	Peak Month	June	June	June	May
	Peak Month Mean Flow (kaf)	4,007	3,914	4,000	3,549
	Peak Month Maximum Flow (kaf)	8,467	8,531	8,678	12,542
	Month at Which Half of Annual Flow (Water Year) is Exceeded	June	June	June	May
Deficit Periods[8]	Maximum Deficit (maf)	28.2	38.4	98.5	254.2
	Maximum Spell Length (years)	8	17	24	48
	Intensity (Deficit/Length) (maf/year)	3.5	2.3	4.1	5.3
	Frequency of 5+ Year Spell Length (Percent)	22%	30%	25%	40%
	Maximum 8-year Deficit (longest in 1906-2007 observed record, maf)	28.2	29.8	50	52.2
Surplus Periods[9]	Maximum Surplus (maf)	22.2	36.2	88	61.1
	Maximum Spell Length (years)	7	15	25	12
	Intensity (Surplus/Length) (maf/year)	3.2	2.4	3.5	5.1
	Frequency of 5+ Year Spell Length (Percent)	28%	15%	18%	<1%
	Maximum 7-year Surplus (longest in 1906-2007 observed record, maf)	22.2	29.2	44	35.3

[8] A deficit period occurs whenever the 2-year running average flow is below the observed average from 1906-2007 of 15.0 maf.
[9] A surplus period occurs whenever the 2-year running average flow is above the observed average from 1906-2007 of 15.0 maf.

10.0 Status and Next Steps

The Water Supply Assessment discussed in this report is a "snapshot" in time, documenting the findings and analysis completed as of January 2011. The research and development program initiated by Reclamation in 2004 resulted in the development of the Paleo Resampled and Paleo Conditioned scenarios. These scenarios were previously described in Appendix N of the Interim Guidelines Final EIS, as was the Observed Resampled scenario. The Downscaled GCM Projected scenario is the newest addition to the set of scenarios and has not been previously used in any Reclamation long-term planning activities. As such, additional analysis and investigation are needed and ongoing to better understand the results of this scenario. The VIC modeling associated with the projected climate forcings suggests changes in streamflows resulting from this scenario are consistent with past efforts, particularly that of Christensen and Lettenmaier, 2007. However, the review of the hydroclimatic data and tools is ongoing and an update to the projections included in this report is likely in Interim Report No. 2. In particular, there are six areas where work is ongoing and will be included in Interim Report No. 2.

1) Application of a secondary bias correction

   Preliminary analyses have indicated that the application of a secondary bias correction to the streamflow results presented in this report is warranted. This conclusion has been made based on two observations. First, the validation simulation of the VIC model results in a 1950-1999 average natural flow at Lees Ferry of 15.33 maf. This is approximately 660 kaf (5 percent) greater than the observed 1950-1999 natural flow of 14.67 maf. This result indicates that a bias exists in the VIC model, the observed historic climate data used in the validation (Maurer et al., 2002, 2007), or both, that results in an *over-estimation* of streamflow.

   Second, the average 1950-1999 natural flow at Lees Ferry resulting from the 112 climate projections (ensemble average) is 14.25 maf. It is expected that these results would be similar to the validation simulation results (15.33 maf). This is because the two sets of climate data used to generate these results are statistically the same on the monthly scale through the application of the first bias correction. This bias correction is applied to adjust a given climate projection for inconsistencies between the simulated historic climate data and observed historic climate data. This result indicates that a bias exists in the climate projection data that results in an *under-estimation* of streamflow.

   There are many components in the methodology to develop streamflow projections from GCM climate projections that may be contributing to the bias in the results discussed above. These components include the VIC model, observed historical climate data, spatial downscaling, and the generation of daily (from monthly) climate data from GCM climate projections. Work is ongoing to further investigate the bias produced by these components and how it may affect streamflow projections. Also under investigation is the most appropriate bias-correction scheme to implement to account for these biases.

2) Investigation of Downscaled GCM Projected sequences that exhibit extremely high flows

A number of sequences in the Downscaled GCM Projected scenario exhibit occasional annual runoff conditions that far exceed any maximum in the observed or paleo records. While it is possible that future climate will expand the magnitude and frequency of extreme events, it is also possible that some projections are simply extreme outliers based on the ensemble. Further investigation is underway to understand and determine whether some projections should be removed from the ensemble when generating future statistics.

3) Separation of Downscaled GCM Projected scenario sequences by SRES emission scenario

The assumption made with respect to the SRES emission scenarios used to drive the GCMs in the Study is that they are all equally likely and can therefore be combined. Projections through mid century are more dominated by the choice of GCM than individual emission scenarios. However, future analysis will demonstrate the range of effects associated with specific SRES emission scenarios, as compared to the combined ensemble as they relate to Basin streamflow.

4) Investigation of increasing Lower Basin runoff

The temporal (monthly to daily) disaggregation (termed weather generation) of the monthly downscaled and bias-corrected GCM projections is necessary to evaluate the hydrologic response in the VIC model. Further investigation is underway to evaluate whether the differences in weather generation schemes would result in different daily storm magnitudes, and thus affect Basin runoff. It is believed that this would only have a potential sizable effect in the Lower Basin areas that are strongly influenced by infrequent and intense storms.

Increases in precipitation in the summer across the southwestern portion of the Basin are consistent with higher precipitation rates likely associated with a more active monsoon season. Investigation is ongoing to determine if these results are also influenced by the weather generation scheme.

5) Documentation of VIC calibration

A major contribution of the Study to advancing future research is complete documentation regarding all the data, methods, and assumptions used to generate the GCM Projected scenario. Work is underway to document the VIC model calibration and validation, biases observed in the historical and future climate data, weather generation scheme, and results. This will likely be included as an appendix in Interim Report No. 2.

6) Assessment of future climate teleconnections

Further documentation of the significance of climate teleconnections and their relationship to streamflow at natural flow location has been conducted and will be included in Interim Report No. 2. In addition, a summary of the most current research relating to the ability of GCMs to capture the large-scale teleconnections that are important to the Basin will be included.

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Disclaimer

The Colorado River Basin Water Supply and Demand Study (Study) is funded jointly by the Bureau of Reclamation (Reclamation) and the seven Colorado River Basin States (Basin States). The purpose of the Study is to analyze water supply and demand imbalances throughout the Colorado River Basin and those adjacent areas of the Basin States that receive Colorado River water through 2060; and develop, assess and evaluate options and strategies to address the current and projected imbalances.

Reclamation and the Basin States intend that this Study will promote and facilitate cooperation and communication throughout the Basin regarding the reliability of the system to continue to meet Basin needs and the strategies that may be considered to ensure that reliability. Reclamation and the Basin States recognize the Study will have to be constrained by funding, timing and technological and other limitations, which may present specific policy questions and issues, particularly related to modeling and interpretation of the provisions of the Law of the River during the course of the Study. In such cases, Reclamation and the Basin States will develop and incorporate assumptions to further complete the Study. Where possible, a range of assumptions will typically be used to identify the sensitivity of the results to those assumptions.

Nothing in the Study, however, is intended for use against any Basin State, the Federal government or the Upper Colorado River Commission in administrative, judicial or other proceedings to evidence legal interpretations of the law of the river. As such, assumptions contained in the Study or any reports generated during the Study do not, and shall not, represent a legal position or interpretation by the Basin States, Federal government or Upper Colorado River Commission as it relates to the law of the river. Furthermore, nothing in this Study is intended to, nor shall this Study be construed so as to, interpret, diminish or modify the rights of any Basin State, the Federal government, or the Upper Colorado River Commission under federal or state law or administrative rule, regulation or guideline, including without limitation the Colorado River Compact, (45 Stat. 1057), the Upper Colorado River Basin Compact (63 Stat. 31), the Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande, Treaty Between the United States of America and Mexico (Treaty Series 994, 59 Stat. 1219), the United States/Mexico agreement in Minute No. 242 of August 30, 1973, (Treaty Series 7708; 24 UST 1968) or Minute No. 314 of November 26, 2008, or Minute No. 318 of December 17, 2010, the Consolidated Decree entered by the Supreme Court of the United States in Arizona v. California (547 U.S 150 (2006)), the Boulder Canyon Project Act (45 Stat. 1057), the Boulder Canyon Project Adjustment Act (54 Stat. 774; 43 U.S.C. 618a), the Colorado River Storage Project Act of 1956 (70 Stat. 105; 43 U.S.C. 620), the Colorado River Basin Project Act of 1968 (82 Stat. 885; 43 U.S.C. 1501), the Colorado River Basin Salinity Control Act (88 Stat. 266; 43 U.S.C. 1951), the Hoover Power Plant Act of 1984 (98 Stat. 1333), the Colorado River Floodway Protection Act (100 Stat. 1129; 43 U.S.C. 1600), or the Grand Canyon Protection Act of 1992 (Title XVIII of Public Law 102-575, 106 Stat. 4669). Reclamation and the Basin States continue to recognize the entitlement and right of each State under existing law to use and develop the water of the Colorado River system.[10]

[10]Reclamation and the Basin States have exchanged letters and are in the process of amending the Contributors' funding agreement to, among other things, document and clarify the intent of the Parties consistent with the above disclaimer.