Lake Powell Pipeline

Draft Study Report 19
Climate Change

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ES-1 Introduction

The Lake Powell Pipeline (LPP) is planned to supply water from Lake Powell, located on the Colorado River, to communities in southwest Utah. This document was prepared to further the understanding of climate change and its potential effects on LPP water supply resources and environmental effects. This document supplements the environmental resource studies associated with water resources in addressing the objectives found in Study Plan 19: Water Supply and Climate Change.

The climate change analysis includes a literature review of existing scientific studies regarding the effects of potential climate change on the hydrology of the Colorado River and existing studies of the paleo-hydrology of the Colorado River. The Bureau of Reclamation (Reclamation) has conducted numerous hydrologic modeling runs using Reclamation's long-term planning model, Colorado River Simulation System (CRSS). A review of these model results using the alternate hydrology generated from tree-ring data was also incorporated into this study report.

Commonly cited studies relating climate change to runoff in the Colorado River Basin are shown in Table ES-1. The models in these studies show similar sensitivity of runoff to precipitation changes. In general, a 10 percent reduction in precipitation results in a 20 percent decline in runoff. However, there is much more variability in hydrology among models with respect to changes in temperature (Hoerling, et al 2009). Hoerling and Eischeid now believe the 45-percent runoff reduction presented in their 2007 report overstates potential losses. This most recent synopsis of climate studies estimates declines in runoff to be between 4 and 18 percent by 2050 depending on the temperature and precipitation scenarios evaluated (Hoerling, et al 2009).

Table ES-1
Projected Changes in Colorado River Basin Runoff or Streamflow in the Mid-21st Century from Recent Studies

Source	Temperature	Precipitation	Year	Runoff Reduction
Christensen, et al (2004)	+3.1°F	-6%	2040-2069	18%
Milly, et al (2005)	--	--	2041-2060	10 to 20%
Hoerling and Eischeid (2007)	+5°F	0	2035-2060	45%
Seager, et al (2007)[2]	--	--	2050	8 to 25%
Christensen and Lettenmaier (2007)	+4.5°F (+1.8 to +5.0)	-1% (-21 to +13%)	2040-2069	6 to 7% (-40 to +18%)
McCabe and Wolock (2007)	Assumed +3.6°F	0	--	17%

Source: WWA 2008
Notes: 1) Values and ranges (where available) were extracted from the text and figures of the references shown.
2) Study does not specifically make projections of Upper Basin runoff or streamflow. Average is over a large area (95°W–125°W, 25°N–40°N) that only partially overlaps with the Upper Basin.

Most studies evaluating system responses to climate induced runoff reductions have focused on scenarios with a 10 percent and 20 percent reduction in flows with no change in precipitation. If only the current shortage management strategies outlined in the Colorado River Interim Guidelines for Lower Basin Shortages EIS (Reclamation 2007) are adhered to, a 10 percent reduction in basin-wide runoff would result in a 26 percent chance that Lake Powell would go dry (reservoir storage completely depleted) at least once by 2056, compared to a 7.5 percent chance with no runoff reductions (Rajagopalan, et al 2009). There is also potential for frequent shortages of 1-million acre-feet (MAF) by 2060 under these conditions (Barnett and Pierce 2009). The Rajagopalan study shows that under a 20 percent flow reduction and current shortage management strategies, the probability of storage depletion by 2056 is 51 percent. A more stringent shortage strategy and demand growth management alternative would reduce risk to between 36 and 43 percent (Rajagopalan, et al 2009). With a 20 percent reduction in flow, Barnett and Pierce 2009 show shortages of 2 MAF/yr occurring 70 to 95 percent of the time by 2060. These values are about 1.5- to 3-times the maximum lower basin delivery reduction explicitly included in the preferred alternative plan of the Interim Guidelines EIS (Reclamation 2007). Although, as noted by the authors of both studies, changes in management practices would certainly occur before Lake Powell would become empty. Rajagopalan suggests that aggressive reuse, conservation, transfers between users, or other measures would be implemented (Barnett and Pierce 2009, NAS 2007).

Tree-ring studies performed within the basin indicate the early 1900s (when Colorado River compact negotiations occurred) were wetter than the preceding centuries and the previous centuries contained many more severe and sustained droughts (Woodhouse, et al 2006). The long-term average annual flow for hydrologic reconstructions at Lees Ferry was 14.7 MAF/year, which is lower than the long-term gaged record mean of 15.1 MAF/year and much lower than the 21 MAF/year flow volume assumed during the Colorado River Compact negotiations. A follow-up study extended the reconstructed annual flows at Lees Ferry back to A.D. 762 (Meko, et al 2007). Results confirmed the previous study conclusions of a drier hydrologic past and showed a mega-drought in the mid-1100s that lasted over 25 years and was characterized by a decrease in mean annual flow of more than 15 percent. If variations in future hydrology are similar to those shown in the tree-ring studies, Barnett and Pierce (2009) conclude that currently scheduled deliveries could not be met, even in the absence of runoff reductions because of climate change.

The Lake Powell Pipeline Hydrologic Modeling- No Additional Depletions Sensitivity Analysis report (Reclamation 2009b) compared scenarios with and without the LPP for each of two hydrologic datasets, observed hydrologic record (DNF) and the alternate, more variable, paleo-conditioned inflows (NPC). A summary of the results outlined in the No Additional Depletions Sensitivity Analysis can be found in the LPP Surface Water Resources Report (MWH 2011). The results from Reclamation's modeling were re-evaluated to compare consequences of the two hydrologic input datasets for the with-pipeline scenario. Results show there is up to 16 percent chance the Lake Powell storage elevation would not exceed the minimum power pool elevation (3,490 feet mean sea level [MSL]) in March after 2050, under the more variable hydrologic regime (NPC) as compared to 3 percent for the DNF flows. The simulated Lake Powell pool elevation dropped to 3,439 feet MSL in the 10^{th} percentile for NPC flows as compared to 3,542 feet MSL for the 10^{th} percentile DNF flows, well above the 3,375 feet MSL minimum proposed intake elevation for the Lake Powell Pipeline. No additional modeling was performed by MWH.

The LPP study area portion of the Virgin River Basin is located in the upper-most part of Reclamation's Lower Basin region. The predicted 2050 to 2079 mean temperature for this area is 2.5 to 2.7^{o}C (4.5 to 5^{o} F) warmer than the 1950 to 1979 historical mean (Reclamation 2009a). This is similar to projected conditions in the Upper Colorado Basin. It is likely that runoff would be reduced for this basin as projected for the Upper Colorado Basin. However, no studies specific to potential future climate induced runoff changes have been performed for the Virgin River Basin and specific predictions regarding the amount of runoff reduction anticipated in the Virgin River Basin have not been made.

Future inflow into Lake Powell is likely to decline because of climate change or natural reversion back to the long-term historical mean observed in the tree-ring studies. Streamflow in the Virgin River is likely to decline because of future climate change, although there have been no published studies to indicate the magnitude of the decline. Reduced inflow to Lake Powell could have detrimental effects on storage levels if more stringent shortage and demand management strategies than included in the Interim Guidelines EIS are not implemented. It is unknown at this time what impacts such management strategies might have on the State of Utah or the LPP project. There are currently no plans to curtail Upper Basin States' water use beyond what is required by the Colorado River Compact.

Chapter 1
Introduction

1.1 Introduction

This draft study report was prepared to support licensing efforts through the Federal Energy Regulatory Commission (Commission) for the Lake Powell Pipeline (LPP) project. The LPP is planned to supply water from Lake Powell, located on the Colorado River, to communities in southwest Utah. This document was prepared to further the understanding of climate change and its potential effects on LPP water supply resources. This document supplements the environmental resource studies associated with water resources in addressing the objectives found in Study Plan 19: Water Supply and Climate Change.

For many years, scientific understanding of Colorado River flows was based on historical gaged records of streamflow. The first gaging stations on the river were established in the 1890s. The stream gage at Lees Ferry was installed in 1921, during the Colorado River Compact negotiations, and has operated continuously since then. It was during this relatively wet period in the measured hydrologic record, that the 1922 Colorado River Compact established the basic apportionment of the river between the Upper and Lower Basins. At the time, it was thought that the average annual flow volume of the Colorado River was about 21 million acre-feet (MAF). The Compact provided for 7.5 MAF of consumptive use annually for each of the basins, plus the right for the Lower Basin to additionally develop 1 MAF of consumptive use annually. Subsequently, a 1944 treaty with Mexico provided a volume of water of 1.5 MAF annually for Mexico. During the period of measured hydrology now available, the river's average annual natural flow has been about 15 MAF/year at Lees Ferry. Greater extensions of the record are essential because important management decisions are based on the knowledge of the river's flows. Extensions of hydrology back before recorded data have been made using tree-ring data. Extensions forward using global circulation models (GCM) to estimate streamflow under potential future climate variability have also been performed by climate researchers. This document reviews studies of hydrologic extensions for the Colorado River near Lake Powell, and identifies their potential impact on LPP reliability. The LPP project would take deliveries from Lake Powell for communities in southwest Utah. Management of Lake Powell under future scenarios represented by extended hydrologic data may affect LPP project operations.

1.2 Methodology

A review of existing scientific literature was performed on potential climate change effects in the region as well as a review of scientific literature on tree-ring studies and paleo-hydrology of the Colorado River. The literature review was limited to information published in peer-reviewed or otherwise authoritative journals and reports. A review of the Reclamation CRSS model results using alternate hydrology generated from tree-ring data also was performed. Using these sources, a range of potential future hydrologic conditions in the Colorado River Basin, including inflow to and outflow from Lake Powell was estimated. Potential impacts on LPP diversions based on management of shortages in Lake Powell were described.

No new river system modeling or analysis was performed as part of this review. All conclusions are based on interpretation of results from previous studies by others.

Chapter 2
Colorado River Water Distributions

2.1 Colorado River Compact

This section provides a brief summary of the Law of the River and Colorado River Compact. More detailed information can be obtained from the U.S. Bureau of Reclamation (Reclamation) website at http://www.usbr.gov/lc/region/pao/lawofrvr.html.

The Law of the River is comprised of compacts (e.g., Colorado River Compact), court decisions and decrees, and regulatory guidelines. The Colorado River Compact (Compact) is one of many documents constituting the Law of the River. It divides the river basin into the Upper Basin (comprised of Colorado, New Mexico, Utah and Wyoming) and the Lower Basin (comprised of Nevada, Arizona and California). At the time of the Compact negotiations, it was thought that the average annual flow volume of the Colorado River was about 21 million acre-feet (MAF). Based on the period of measured hydrology now available, the average annual natural flow is about 15 MAF at Lees Ferry. The Compact requires the Upper Basin states to not deplete the flow of the river below an average of 7.5 MAF per year at Lees Ferry during any periods of ten consecutive years to make sure the Lower Basin states receive 7.5 MAF of consumptive use. Additionally, the Compact provides the right for the Lower Basin to develop another 1 MAF per year of consumptive use. A 1944 treaty with Mexico provides another 1.5 MAF of Colorado River water annually for Mexico. The Upper Colorado River Basin Compact of 1948 apportioned 7.5 MAF per year among the Upper Basin states based on a percentage of available flow. The State of Utah is allotted 23 percent of the Upper Basin's 7.5 MAF, or 1.73 MAF per year. Neither the State of Utah or the other Upper Basin States believe the Colorado River will yield 7.5 MAF per year to the Upper Basin. The Upper Basin States are now operating on a Colorado River yield of 6.0 MAF per year. The State of Utah's share of the current Colorado River yield at 23 percent is approximately 1.4 MAF per year.

2.2 Interim Guidelines for Lower Basin Shortages

The recently adopted shortage guidelines, described in the preferred alternative of the *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* (Reclamation 2007), were developed in response to the eight-year drought on the Colorado River from 2000-2007. The guidelines assist Reclamation in managing the Colorado River during drought periods and low reservoir conditions. Under these guidelines, shortages were imposed on the Lower Basin States by themselves based on Lake Mead elevations shown in Table 2-1.

Table 2-1
Interim Shortage Guidelines

Lake Mead Elevation on January 1 (mean sea level)	Shortage Imposed on Lower Basin States and Mexico (acre-feet)
1,075 feet	400,000
1,050 feet	500,000
1,025 feet	600,000
<1,025 feet	Discussion of further measures consistent with the Law of the River

Notes: From Reclamation 2007

The shortages shown in Table 2-1 would have been greater but Arizona refused to agree to a greater shortage, because they take 97 percent of the shortage and Nevada takes the remaining 3 percent. The Upper Basin States continue to make their full Compact deliveries to the Lower Basin and Mexico under the interim shortage guidelines shown in Table 2-1.

The United States Secretary of the Interior is the water master for administration of the compacts affecting the Colorado River. Reclamation is the Department of the Interior's agent for operating federal facilities on the Colorado River and administering the Secretary of the Interior's actions under the compacts. Therefore, Reclamation was the lead federal agency in preparing the Interim Guidelines EIS (Reclamation 2007).

To avoid curtailment of uses in the Upper Basin and minimize the shortages in the Lower Basin, a strategy for operating Lakes Powell and Mead was outlined in the EIS (Reclamation 2007). The Interim Guidelines for operating Lake Powell are summarized in Table 2-2. Under this strategy, the January 1 projected system storage and reservoir water surface elevations are used to determine releases from Lake Powell. In water years when Lake Powell is projected to be at or above the specified elevations in the EIS (ranging from 3,636 to 3,666 ft, MSL) or to have greater volume than that of Lake Mead, Lake Powell releases greater than 8.23 MAF per year to equalize storage with Lake Mead. Otherwise it releases only 8.23 MAF per year. If Lake Powell projected contents are below 3,575 feet MSL and above 3,525 feet MSL, and Lake Mead elevations are greater than 1,025 feet MSL, only 7.48 MAF per year are released from Lake Powell.

Table 2-2
Interim Guidelines for Operating Lake Powell

Lake Powell Elevation (feet, MSL)	Lake Powell Operation Relative to Lake Mead	Lake Powell Live Storage (MAF)
3,700	Equalize, avoid spills or release 8.23 MAF	24.32
3,636-3,666[1]	Release 8.23 MAF; if Lake Mead < 1,075 feet, balance contents with a min/max release of 7.0 and 9.0 MAF	15.54-19.29
3,575	Release 7.48 MAF; release 8.23 MAF if Lake Mead < 1075 feet	9.52
3,525	Balance contents with a min/max release of 7.0 and 9.5 MAF	5.93
3,370		0

Notes: 1) Elevation based on Table 2.3-2 of Reclamation 2007
2) From Reclamation 2007, Appendix S

2.3 Interim Guidelines EIS Hydrology

Reclamation based its hydraulic and hydrologic analyses and CRSS modeling on the re-sampled historical record (Reclamation 2007). The Interim Guidelines EIS did not incorporate forecasts of future climate variability into its modeling for the main body of the EIS; however, it incorporated a sensitivity analysis of the hydrologic resources to hydrologic scenarios derived from alternative methods in the EIS appendix. Three methods were used to generate future hydrologic inflow sequences with increased hydrologic variability relative to the historical record. The Direct Natural Flow Record (DNF) was generated using a stochastic method based on the historic gaged record. The Direct Paleo technique (DP) uses streamflow reconstructions from tree-ring chronologies directly to generate future hydrologic sequences. The sequence 1 paleo-reconstruction from Meko et al. 2007 was used. The DNF and DP hydrologic inflow scenarios are re-sampled with the Index Sequential Method (ISM-stochastic method), which guarantees year to year hydrologic inflow statistics that are nearly identical to each other. The nonparametric paleo-conditioning technique (NPC) extracted paleo-hydrologic state information from streamflow reconstructions (Woodhouse 2006) and generated flow magnitudes by conditionally choosing from the historical record. The NPC hydrologic inflow is generated with stochastic methods that do not generate identical hydrologic inflow scenario statistics on a year to year basis.

When comparing the four hydrologic inflows to the likelihood of being below the minimum power pool elevation (3490 feet MSL) for Lake Powell, the DNF shows nearly no chance of falling below, where the NPC indicates the highest likelihood of occurrence at 26 percent after 2055. The highest probability of shortage for lower Basin states and Mexico would occur after 2055, where the DP simulates an 80 percent chance of shortages; DNF, 69 percent; and NPC 62 percent (Reclamation 2007, Appendix N, Attachment A). These differences are noted in the sensitivity analysis, and the DNF hydrology was used for the modeling of alternatives in the final EIS. Thus, post-EIS commenters argue that the shortage guidelines were based on the assumption that hydrology for “the 20th century will be replicated in the 21st century, an assumption at odds with the tree ring data” (Barnett and Pierce 2009b).

Chapter 3
Literature Review

3.1 Introduction

The LPP project would take deliveries from Lake Powell for communities in southwest Utah. As the Colorado River feeds Lake Powell, changes in Colorado River flow could directly impact storage in Lake Powell. Under most drought scenarios, the most secure water rights are from reservoirs at the downstream end of river system. In the Colorado River, water shortages are likely to occur first on the senior water rights high in the river system. If the Upper Basin States are required to curtail uses to meet Lower Basin obligations, there could be Upper Basin water in Lake Powell most of the time because any Upper Basin water in Lake Powell can't be diverted except through the Lake Powell Pipeline project. The potential impact of climate change on the hydrology of the Colorado River has been an important subject in scientific investigation for many years because so many communities rely on water deliveries from the Colorado River/Lake Powell system.

The Climate Technical Work Group Report (Reclamation 2007), which was prepared as Appendix U for the *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead,* includes a thorough literature review of the climate science in the Colorado River Basin. Many pertinent studies utilizing paleo-reconstructed hydrology for the Colorado River Basin have been performed. Reclamation's Research and Development Office commissioned the Technical Service Center Water Operations and Planning Support Group to perform a comprehensive literature review and literature synthesis that was region-specific within the United States to ensure efficient and consistent discussion of climate change implications in planning documents (Reclamation 2009a).

According to Reclamation (2009a), the Upper Colorado Region (which includes Lake Powell) appears to have become warmer during the 20th century. Data available from the Western Climate Mapping Initiative indicate the 11-year mean temperature has increased during the 20th century and is roughly 1.2° C (2.2º F) warmer for the Upper Colorado River Basin and 1.7° C (3.1º F) warmer for the Lower Colorado River Basin than it was a hundred years ago (difference computed is the 1996 to 2006 mean minus the 1896 to 1906 mean, Reclamation 2009a). According to Hamlet et al. 2005 and Stewart et al. 2004, it also appears that snowpack is decreasing and runoff is occurring earlier in the Upper Colorado River Basin than it did in the past. Mote et al. 2005 found widespread declines in springtime snowpack in much of the North American West over the period 1925 to 2000, especially since mid-century. However, the authors did not include the Upper Colorado River Basin. Snowpack is important in determining the seasonality of natural runoff. In many Upper Colorado Region headwater basins, the precipitation stored as snow during winter accounts for a significant portion of spring and summer inflow to lower elevation reservoirs.

There is high confidence warming would continue into the future; however, there is less consensus regarding future precipitation. The coarse spatial resolution of climate models limits their ability to represent topographic effects related to snowfall, snowpack evolution, and regional precipitation patterns (Grotch and MacCracken 1991; Giorgi and Mearns 1991; Pan et al. 2004; Reclamation 2007). Studies have been performed that use downscaling techniques to recover some of this spatial detail. Others have analyzed various scenarios involving the impacts of temperature and precipitation changes on the Colorado River system hydrology, and assess operational impacts for the Colorado River Storage System.

3.2 Climate Change Studies

In 1999, Peter Gleick and Elizabeth Chalecki performed a literature review of all studies regarding the impacts of climate change on water resources in the Colorado River Basin. Subsequently, the climate technical work group report reviewed the top six major studies regarding the effects of climate change on runoff in the Colorado River between 1979 and 2007. The earliest studies use hypothetical temperature and precipitation changes evaluated with historical analogies and regression approaches. In 1979, Charles Stockton of the University of Arizona Laboratory of Tree-Ring Research and William Boggess, wrote a report for the U.S. Army Corps of Engineers Engineering Research Center. The authors used four different climate change scenarios that combined +/- 2° C temperature change with +/- 10 percent change in precipitation. They used these scenarios in conjunction with Walter Langbien's (Langbien 1949) relationships between temperature, precipitation and runoff. In the Upper Colorado basin, the authors found decreased runoff with a warmer/drier scenario as well as a warmer/wetter scenario. The warmer temperatures significantly increased evapotranspiration rates such that the increase in precipitation could not accommodate the runoff reduction. The decrease in runoff for both scenarios was about 5 MAF or 33 percent of average annual flow at Lees Ferry. Revelle and Waggoner's 1983 report for the National Academy of Sciences also utilized the Langbien 1949 relationships. The study generated a multiple linear regression between Upper Basin temperature and precipitation, and unimpaired flow at Lees Ferry. Their equation, with an r^2 of 0.73, showed that a 2° C increase in temperature alone would reduce runoff by 29 percent. A 2° C increase combined with a 10 percent decrease in precipitation would reduce flows by 40 percent at Lees Ferry.

By the late 1980s, regression analyses were replaced by physically based models. Studies by Linda Nash and Peter Gleick published in 1991 and 1993 looked at future Colorado River flows under various climate change scenarios. In 1991, the authors used hypothetical temperature and precipitation scenarios as well as scenarios produced by general circulation model (GCM) simulations. These scenarios were used as meteorological inputs to the National Weather Service River Forecasting System (NWSRFS) hydrologic model for three sub-basins with limited human influence of the Colorado River Basin above Lake Powell as well as for a two-elevation aggregated model to simulate inflows for Lake Powell. In 1993, the authors added a "transient" climate study, a direct GCM runoff analysis. To investigate how flow changes would affect reservoir operations and system reliability, the USBR CRSS operations model was also utilized as part of the 1993 study. A 2° C increase in temperature alone reduced runoff by 4 to 12 percent and a 4° C increase in temperature reduced runoff by 9 to 21 percent. The most extreme runoff reduction produced by GCM model inputs (large regional temperature increase and no precipitation increase) resulted in a 10 to 24 percent reduction in runoff. This was the first study to suggest that temperature increases would shift the seasonality of runoff in the Colorado Basin to increased winter runoff and decreased spring runoff, because of more winter precipitation falling as rain and a faster, earlier spring snowmelt. It was also the first study to indicate that small, steady reductions in streamflow would manifest in large declines in system storage. A 10 percent reduction in runoff caused average Lake Powell storage to decline by 30 percent relative to historical levels. In both the 10 percent and 20 percent runoff reduction scenarios, Lake Mead is completely drained in some years. Of course, these results are dependent upon assumptions made regarding shortage allocations, reservoir starting contents and compact deliveries during extended drought conditions as well as other factors. Under real operations, it is unlikely Lake Mead would be drained because the Lower Basin States would implement more stringent water shortage criteria.

Christensen, et al 2004, of the University of Washington Department of Civil and Environmental Engineering, used the National Center for Atmospheric Research Parallel Climate Model (PCM) to simulate runoff and operations on the Colorado River during three future 21st century periods. At the time, PCM simulations showed less temperature sensitivity to the same greenhouse gas emissions as did other GCMs. Monthly temperature and precipitation output from the PCM simulations was downscaled to 1/8 degree daily data and used as input for the Variable Infiltration Capacity (VIC) hydrologic model. VIC simulates snowpack and snowmelt, soil moisture, evapotranspiration, runoff and baseflow. Runoff and baseflow are then routed through a flow network to calculate streamflow. VIC output was then used as input for the Colorado River Reservoir Model (CRRM) operations model. Results of the study are shown in Table 3-1. Because the CRRM simulation periods were run in sequence, initial storage in Periods 1, 2, and 3 (which are 13, 43, and 73 years, respectively, after the initial year of the future runs) differ from each other. Thus, system performance under these three simulated periods differs. The authors state that this reflects the evolution of climate change impacts on system performance throughout the simulated periods. Storage in the model is simulated using four "equivalent" reservoirs: Navajo Reservoir, Flaming Gorge Reservoir, Lake Powell, and Lake Mead.

Table 3-1
Annual Average Temperature, Precipitation, Runoff, Storage and Hydropower Results for the Upper Colorado River Basin

Period	Temperature Change (°C)	Precipitation	Runoff	Storage	Hydropower
Historical	n/a	354 mm/yr	45 mm/yr	39.9 BCM/yr	8,123 hr/yr
Control	+0.5	–1%	–10%	–7%	–16%
2010-39	+1.0	–3%	–14%	–36%	–56%
2040-69	+1.7	–6%	–18%	–32%	–45%
2070-2098	+2.4	–3%	–17%	–40%	–53%

Notes: From Christensen, et al 2004

Niklas Christensen and Dennis Lettenmaier published an article on future Colorado River flows in 2007. Their study utilized GCM model results prepared for the 2007 IPCC Fourth Assessment (IPCC). The authors used 11 major climate models and two different future emission scenarios. (a high scenario-A2 and a relatively low scenario-B1). The approach from Christensen et al. 2004 was utilized with the expanded suite of climate models. VIC was re-calibrated with an additional 10 years of data. Results for temperature, precipitation and runoff are shown in Table 3-2. Dennis Lettenmaier reran this 2007 study in 2009 with another version of downscaled future data and results changed from a 5 percent to a 10 percent streamflow reduction by 2050 (Hoerling, et al 2009).

Table 3-2
Average Ensemble Changes Relative to Historic 1950 to2099 Modeled Base Case for the Upper Colorado River Basin

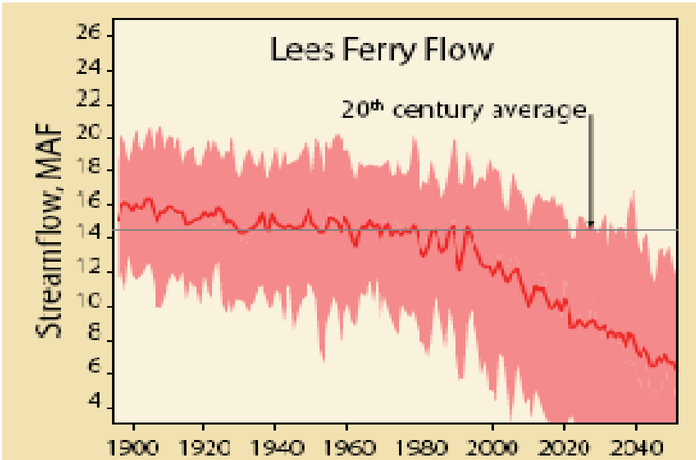
Period	Temperature		Precipitation		Runoff		Storage	
Historic	10.5° C		354 mm/yr		45.2 mm/yr		41.8 BCM	
	B1	A2	B1	A2	B1	A2	B1	A2
2010-39	+1.3	+1.2	+1%	-1%	0%	-1%	+1%	+4%
2040-69	+2.1	+2.6	-1%	-2%	-7%	-6%	-5%	0%
2070-99	+2.7	+4.4	-1%	-2%	-8%	-11%	-10%	-12%

Notes: From Christensen and Lettenmaier 2007

Results from the operations model, CRRM (which was modified to reflect how Lower Basin shortages should be tied to Lake Mead levels) showed higher reservoir levels than those reported in the 2004 study. However, the authors state that because of the large ratio of storage to inflow in the basin, neither an increase in total storage nor a change in operating policies would likely mitigate the storage impacts under declining inflows.

Martin Hoerling and Jon Eischeid published findings in the January/February 2007 issue of Southwest Hydrology magazine (not a peer-reviewed journal). The authors utilized the Palmer Drought Severity Index (PDSI) to create a simple linear regression for flow at Lees Ferry. The regression was used to downscale future PDSI to Lees Ferry flows. PDSI was calculated for each of 42 climate simulations spanning 1895 to 2060, using multiple runs of 18 different coupled ocean-atmosphere-land models. The models used known changes in atmospheric constituents and solar variations from 1895 to 2000 and a business as usual assumption for greenhouse gas emissions after 2000. The models produced a realistic range of PDSI drought events during the 20th century, and for the future they produce surface moisture conditions that denote a progressively more arid climate and severe drought conditions. The average of all models used showed negligible net change in precipitation. The variability in precipitation among the models was considerable, yet even some higher precipitation years resulted in drier periods due to the effect of heat-related moisture loss. The average temperature during the 2006 to 2030 simulated period increased by 1.4° C over the 1895 to 2005 mean. For the 2035 to 2060 period, average temperatures increased 2.8° C. Results for streamflow showed reductions below the current consumptive use demand on the river within the next 20 years. Relative to the 1990 to 2005 mean flow of 13 MAF, the 42-run average predicts a 25 percent decline in streamflow during the 2006 to 2030 simulated period, and a 45 percent decline during the 2035 to 2060 simulated period (Source: From Hoerling and Eischeid, 2007. Figure 3-1). The dark red curve denotes the 42-run average, and the clouded area on Figure 3-1 describes the 10 to 90 percent range of individual simulations.

Because most runoff comes from a small part of the Upper Colorado basin, above 8,000 feet and runoff contributions from the individual sub-basins vary considerably, basin models at large scales (Milly, et al 2005, Hoerling and Eischeid 2007, Seager ,et al 2007) likely overstate declines in runoff. The Hoerling study was revisited in 2009 and Hoerling and Eischeid now believe the 45 percent runoff reduction overstates potential losses, yet runoff declines are still expected (Hoerling, et al 2009).



Source: From Hoerling and Eischeid, 2007.

Figure 3-1
Modeled 1895 to 2050 Lees Ferry Annual Streamflow

McCabe and Wolock 2007 used a water-balance model to evaluate potential effects of specific levels of atmospheric warming on water-year streamflow in the Colorado River and evaluated their results in the context of long-term (1490 to 1998) historical tree ring reconstructions (Woodhouse, et al 2006). Their results show that under a 2° C temperature increase scenario, 1901 to 2000 mean annual flow is reduced by 17 percent, a level which is unprecedented in the 1490 to 1998 reconstructed flows period. Furthermore, the calculated Colorado Compact failure rate increased from 0.07 to 0.37 under this scenario.

Three additional studies that feature GCM projections for the American Southwest in general are included in the Literature review (Reclamation 2007). These utilize GCM runoff as part of a larger scale study and do not have the higher resolution, more detailed representation of the previously described studies. However, their results are worth mentioning. First, Milly, et al 2005 and a later addendum (unpublished as of 2007), found that greater than 90 percent of the GCM simulations show future Colorado River Basin runoff reductions of 10 to 30 percent by 2060. Seager, et al 2007 used many of the same GCMs and runoff information as Milly, et al 2005. Seager's study was specific to the "American Southwest" (the area included land from Brownsville, TX to Lincoln, NE to Eureka, CA, including parts of Mexico). Eighteen of the nineteen models Seager, et al 2007 evaluated showed a drying trend in this area. Finally, the Fourth Assessment of the Intergovernmental Panel on Climate Change released its report in the spring of 2007 (IPCC 2007). In this report, it is predicted that North American snow season lengths and snow depth are very likely to decrease, except in the northernmost part of Canada. In the southwestern USA, warming would likely be greatest in the summer and mean annual precipitation is likely to decrease.

Reclamation (2009a) summarized studies pertaining to the effects of climate change on ecosystem function in the river basin, including impacts on vegetation and aquatic resources. In a separate chapter of the document, a qualitative summary of potential climate change impacts on various resources categories such as surface water supplies, flood control, hydropower, fisheries, surface water quality and ground water is provided.

3.3 Climate Change and Lake Powell Studies

Two studies came out after the Colorado River Interim Guidelines EIS (Reclamation 2007) that looked specifically at potential climate change affected hydrology in the Colorado River and its effects on storage in Lake Powell and Lake Mead. These studies were motivated by the fact that the Interim Guidelines EIS did not account for anthropogenic climate change, despite the lengthy literature review of studies showing that climate change would reduce streamflow in the Colorado River. Furthermore, the EIS incorporated the assumption that hydrology for "the 20th century will be replicated in the 21st century, an assumption at odds with the tree ring data" (Barnett and Pierce 2009b).

First, Barnett and Pierce 2008 published a paper entitled "When Will Lake Mead Go Dry?" This study used a water budget and two types of flow analyses. The first flow analysis assumed 10 percent and 30 percent reductions in the 1906 to 2004 average annual runoff passing the Lees Ferry gage. The results showed storage to be depleted in 2030 for the 30 percent flow reduction and 2047 for the 10 percent flow reduction scenario. The second flow analysis included natural flow variability at Lees Ferry developed from statistically modeled simulations based on historical gaged data and flow estimates from approximately 1,250 years of tree ring data. The results showed that even without climate change, there is a 50 percent chance the system would go dry by 2037. There is a 50 percent chance of the system going dry by 2028 with natural variability and a 20 percent reduction in flows.

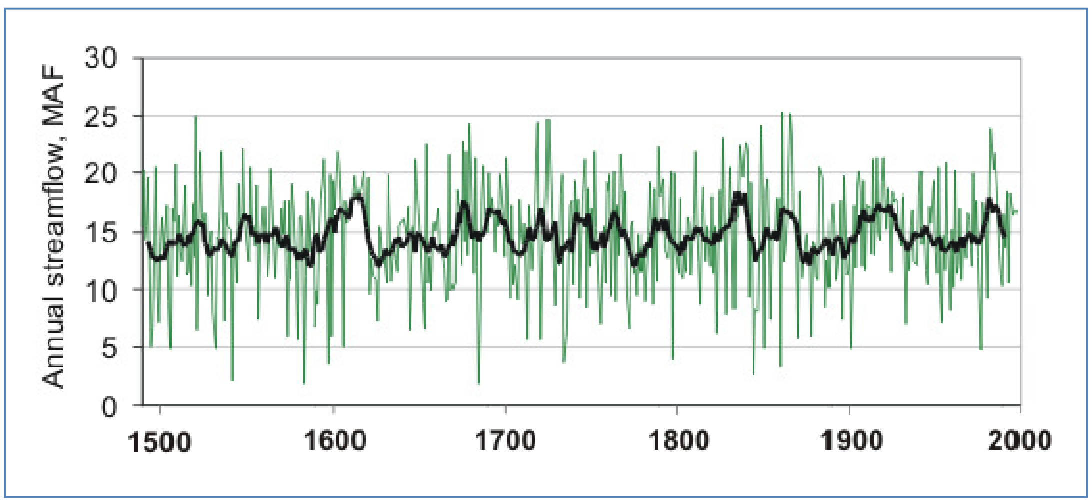
This study elicited several comments from scientists in this field, along with published responses and a follow-up paper (Barsugli et al. 2009, Barnett and Pierce 2009a, Barnett and Pierce 2009b). The follow-up paper by Barnett and Pierce entitled "Sustainable water deliveries from the Colorado River in a changing climate" was published in PNAS (Proceedings of the National Academy of Sciences). This study utilized an improved water budget model as well as the "preferred alternative" schedule of delivery cuts from the Interim Guidelines shortage policies (Reclamation 2007). When using the same inflow assumptions as Barnett and Pierce 2008, the improved models resulted in a 4 to 10 year delay in dry-up, depending on the scenario. Again, they analyzed both 20th century flows as well as paleoclimate flows based on tree ring reconstructions at Lees Ferry. Results based on 20th century flows show that in the absence of predicted climate change, delivery shortfalls of 0.61 MAF/yr would occur 40 percent of the time by 2060. With a 10 percent reduction in Colorado River runoff, shortages would begin to occur by 2040 and reach 1 MAF/year 70 to 95 percent of the time by 2060. With a 20 percent reduction in flow, shortages would begin to occur by 2025 and average 2 MAF/year 70 to 95 percent of the time by 2060. These values are about 1.5- to 3-times the maximum lower basin delivery cut explicitly included in the preferred alternative plan (Reclamation 2007). Reducing scheduled deliveries would increase these values and the resiliency of the system. Using paleoclimate inflows without reducing runoff to account for climate change indicates shortages occurring by 2025. When inflows are also reduced by 10 percent, simulated shortages begin to appear immediately. The authors include a caveat there is substantial uncertainty of the magnitude and timing of shortages when using the paleoclimate flows, as there is no robust consensus to what the realistic mean low inflow should be.

At the same time of the first Barnett and Pierce study (published after Barnett and Pierce 2008 but before the comments from Barsugli et al. 2009), Rajagopalan, et al 2009 used a heuristic model that combined Lake Powell and Lake Mead water budgets to assess the storage response to reduced hydrologic inflow due to climate change. The authors also evaluated several shortage management alternatives to determine if there would be a way to successfully mitigate predicted shortages. Results indicate a 26 percent chance for the system to go dry (reservoir storage completely depleted) at least once by 2056 under a scenario of 10 percent flow reduction and current shortage management strategies. Under a 20 percent flow reduction and current shortage management strategies, the probability of storage depletion is 51 percent. For the 20 percent flow reduction, more stringent shortage strategy and demand growth management alternatives reduce risk to between 36 and 43 percent. Thus the author suggests that more aggressive shortage policy strategies may be required.

3.4 Paleoclimate Studies

Equally important to climate change studies pertaining to future flows have been the paleoclimate studies pertaining to past flows. These studies reveal that long-term historical flows that may have been drier and more variable in nature than is currently seen. For many years, scientific understanding of Colorado River flows has been based on historical gaged records of the river's flow. The first gaging stations on the river were established in the 1890s. The stream gage at Lees Ferry was installed in 1921, during the Colorado River Compact negotiations, and has operated continuously since then. At the time of the compact negotiations, it was thought that the average annual flow volume of the Colorado River was about 21 million acre-feet (MAF). Based on the period of measured hydrology now available, the river's average annual natural flow is about 15 MAF at Lees Ferry. Greater extensions of the record have been made because important management decisions are based on the knowledge of the river's flows. Annual growth rings in trees at lower elevations can reflect moisture availability. Therefore, tree-ring data can be used to reconstruct records of historical river flows. Using data from coniferous tree species with long life spans in the Colorado River region, flow records dating back several centuries have been reconstructed (NAS 2007).

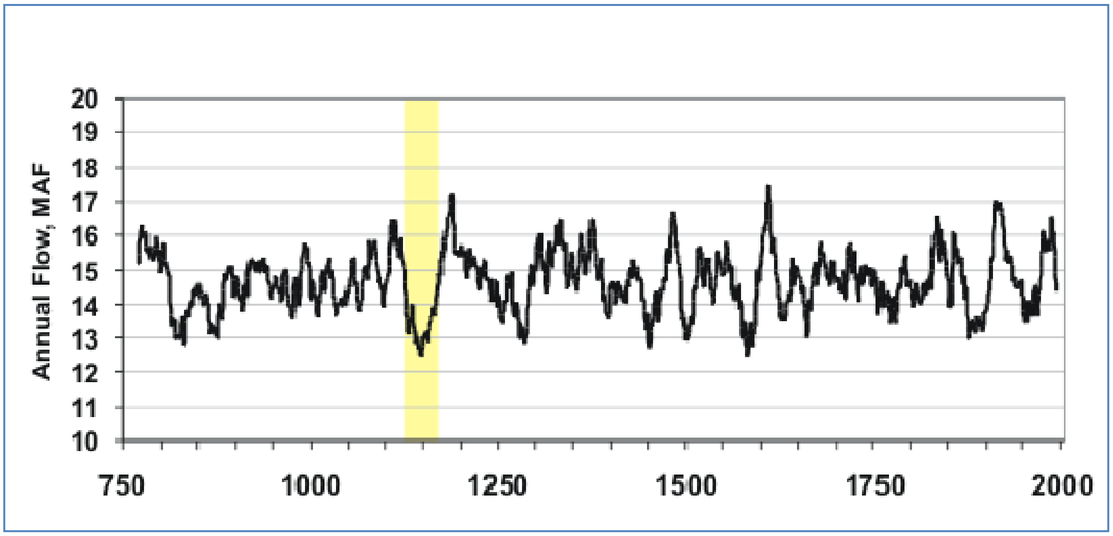
Connie Woodhouse, Stephen Gray, and David Meko of the University of Arizona's Laboratory of Tree-Ring Research (LTRR) used the network of new tree-ring chronologies to generate updated reconstructions of streamflow for the Colorado River. They reconstructed the natural flows at 10 main gages in the basin, including Lees Ferry. Multiple reconstructions were generated for each gage and different techniques were used to process and calibrate the data (Woodhouse, et al 2006). Results showed that the early 1900s (when Colorado River compact negotiations were occurring) were wetter than the preceding centuries and that the previous centuries contained many more severe dry years. The long-term average annual flow was 14.7 MAF/year which is lower than the long-term gaged record mean of 15.1 MAF/year (Source: From Woodhouse, et al 2006).



Source: From Woodhouse, et al 2006

Figure 3-2
Lees Ferry Reconstruction of Annual Streamflow, 1490 to 1997
(annual values in green and 10-year running mean in black)

In 2007, Meko, et al released a study that extended the reconstructed annual flows at Lees Ferry back to A.D. 762. The authors used tree rings from remnant preserved wood. This reconstruction used a new methodology and a set of "nested" models to take advantage of all of the tree-ring data available for different periods of time. Results showed a drought in the mid-1100s that lasted over 25 years characterized by a decrease in mean annual flow of more than 15 percent (Source: From Meko, et al 2007).

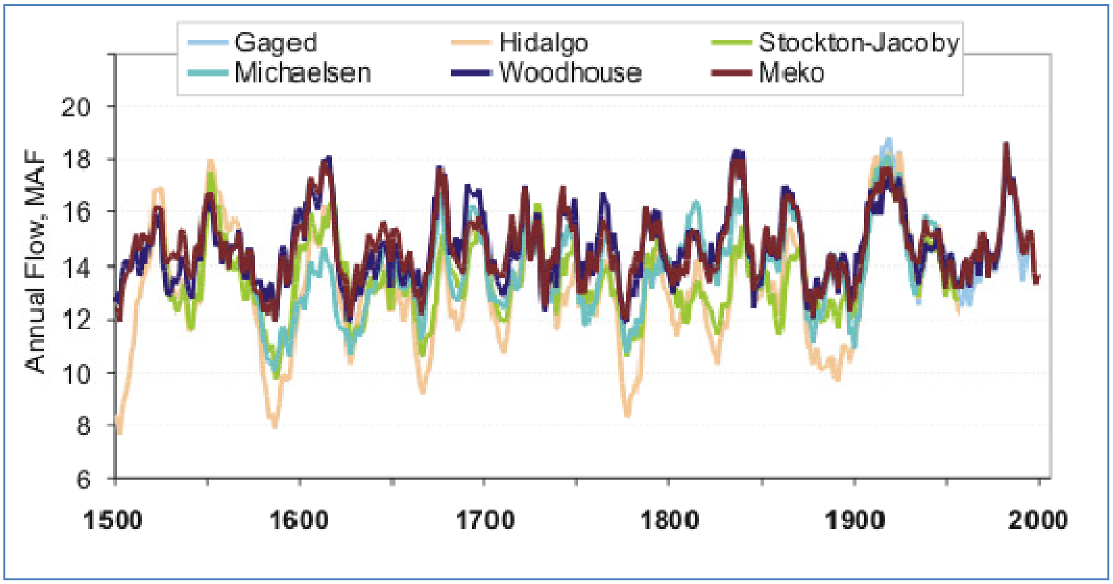


Source: From Meko, et al 2007.

Figure 3-3
Reconstruction of Streamflow for the Colorado River at Lees Ferry, 762 to 2005
(20-year running mean) (The yellow bar highlights the severe and sustained mid-1100s drought)

The Western Water Assessment group performed a comparison of these two Lees Ferry reconstructions as well as some older studies (Stockton and Jacoby 1976, Michaelsen 1990, Hidalgo 2000). They found that the reconstructions generally agree on representations of wet and dry periods on the Colorado River; however, some of the long-term means and the specific magnitudes of wet and dry periods were quite different (Source: The Woodhouse, et al "Lees-A" reconstruction, from WWA 2010.

Figure 3-4). Reconstructions over the last century are very comparable to one another as they are calibrated to very similar gage records during this period. Prior to that, specific input data and methods used to generate the reconstructions differ among studies. These differences include the set of tree-ring data used to generate the reconstruction (locations, species, etc.), the statistical treatment of the tree-ring chronologies and the regression approach used for the modeling, among other things. No reconstruction is “right”; however, they are all plausible estimates of past streamflow, with uncertainties attached to each of the estimates. In general, the most recent reconstructions, having a longer calibration period (90 to 100 years) than the previous reconstructions (50 years) are likely to be more reliable (WWA 2010).



Source: The Woodhouse, et al "Lees-A" reconstruction, from WWA 2010.

Figure 3-4
Ten-Year Running Means of Four Lees Ferry Streamflow Reconstructions and the U.S. Bureau of Reclamation Natural (gaged) Flow Record

These studies indicate the historical observed data was recorded during a relatively wet period. Evaluating the Colorado River's ability to meet future deliveries based only on 20th century flows is not conservative. If the future climate were to revert to average conditions seen in the tree-ring records, inflows to Lake Powell would be reduced compared to the past century. Couple this with possible reductions in runoff caused by predicted climate change, and the results could be even more severe.

3.5 Studies Currently Being Conducted

Climate change effects in the Colorado River Basin will continue to be a topic of interest for many years to come. At the time this document was authored, there were three prominent studies being conducted that address climate change and hydrology in the Colorado River Basin. These include the Joint Front Range Climate Change Vulnerability Study (JFRCCVS), the Colorado River Water Availability Study (CRWAS) and the Colorado River Basin Water Supply and Demand Study, being conducted as part of the Basin Study Program. Of these, only the CRWAS has released a draft report. None of the studies have been finalized.

3.5.1 Joint Front Range Climate Change Vulnerability Study

The JFRVVVS is a regional planning effort amongst water providers and agencies along the Front Range of Colorado. Much of the water supply for the Front Range comes from trans-basin diversions from the Colorado River Basin, therefore, it was included in this study. The main objective of the study was to determine the sensitivity of streamflow at pertinent gages within the basins to projected climate variability. For the Upper Colorado River Basin, nine gages were selected for evaluation. Five climate scenarios were selected from the 112 GCM scenarios available for this area. The selected scenarios were downscaled and bias corrected. Also, temperature and precipitation perturbations were performed on the historical record to create additional scenarios for evaluation. The scenarios were then run through two separate hydrology models. These models, the Water Evaluation and Planning (WEAP) Model and the Sacramento Soil Moisture and Snow-17 Model, bridge the gap between the climate change projections and the effects on local streamflow. Results of this study may be used in the individual planning and operations models of the water providers for decision making purposes. A draft report of this study was expected in fall 2010 (Basdekas, 2010).

3.5.2 Colorado River Basin Water Supply and Demand Study

Under the SECURE Water Act, Reclamation is required to perform and evaluate climate change impact studies in all of Reclamation's basins. One of the Basin Study Programs currently under way is the Colorado River Basin Water Supply and Demand Study. The purpose of the 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 Basin States that receive Colorado River water for approximately the next 50 years, and to develop and analyze adaptation and mitigation strategies to resolve those imbalances." Specifically, it aims to characterize water supply and demand imbalances, under varying conditions, from both historical climate variability and potential climate change variability. Also, it plans to develop recommendations and assess potential strategies to resolve these imbalances. Strategies already identified include modifying operating guidelines, building new facilities or modifying existing facilities, modifying or developing new conservation programs and modifying or developing new supply enhancement programs. The strategies evaluated will be prioritized and recommended for future feasibility studies or other future actions. Potential legal and regulatory constraints will be considered for all strategies identified and considered. A report describing the findings of current and future water supply and demand assessments was expected by September 2010 (Reclamation 2010).

3.5.3 Colorado River Water Availability Study

The CRWAS study submitted a draft of their Phase I report in spring of 2010. The study purpose was to assess the adequacy of Colorado's water supplies. The study examined future water availability using records of historical water supplies, extended hydrology using tree ring studies, and potential hydrologic conditions that may exist because of predicted climate change. Similar to the JFRCCVS, five climate projections were selected that were representative of the distribution of the 112 available CCM projections for evaluation. These projections were run through the Variable Infiltration Capacity (VIC) hydrology model and downscaled for use in the operations model. The effects of compact constraints on water use were also considered. In addition, the effect of forest disturbance, such as fire, disease or logging as it pertains to water supply, was evaluated.

The different hydrologic time-series were incorporated into the Upper Colorado River StateMod to determine how much water might be available to Colorado for future consumptive uses given certain compact assumptions. Demands were based on current consumptive and non-consumptive water demands under current water management operating rules. The range of climate altered hydrology was very large, and included both significant increases and decreases in future streamflow. The study notes there are limitations to the science of future climate change projections on hydrology. Thus, the results indicate a broad range of uncertainty in the water available for future consumptive uses. Table 3-3 shows the range of potential outcomes of the amount of water available for future consumptive use given the two bounding values of the compact assumptions used and the different hydrologic cases presented in the draft report (AECOM 2010).

Table 3-3
Water Available for Future Consumptive Use by Colorado[1]
(MAF)

Hydrology Used	Water Available for Future Consumptive Use[2] (MAF)
Modeled Study Period (1950-2005)	0.43—0.79
Extended Historical Hydrology	0.48—0.89
Alternate Climate Projections (2040)	0—1.0

Notes:
[1]From AECOM 2010, Figure 3-37
[2]Includes CRSP Evaporation

Chapter 4
CRSS Model Studies of Climate Change Effects on Lake Powell

4.1 Overview

The State of Utah contracted with Reclamation to perform additional simulations with its CRSS model to support evaluation of the LPP. The model and hydrologic inflows analyzed in the Interim Guidelines EIS (Reclamation 2007) are summarized in Section 0. The model simulates storage effects on Lake Powell and streamflow effects on the Colorado River with a monthly time-step (Reclamation 2009b). Two input hydrology scenarios similar to those used in the Interim Guidelines EIS were evaluated:

- Direct Natural Flow, Index Sequential Method (DNF) – Developed from the observed streamflow record from 1906 to 2006. This natural flow record was developed by Reclamation and is used extensively in their hydrologic modeling and EISs. In this inflow scenario, the existing historical record of natural flows was used to create a number of different future hydrologic sequences using a resampling technique known as the Indexed Sequential Method (ISM). The ISM results in a number of different future hydrologic sequences that allows calculation of uncertainty. This scenario was the primary inflow dataset used for the 2007 Shortage EIS. DNF results in 101 simulated outcomes for each month, which are summarized using non-parametric statistics including the 10^{th}, 50^{th}, and 90^{th} percentiles.

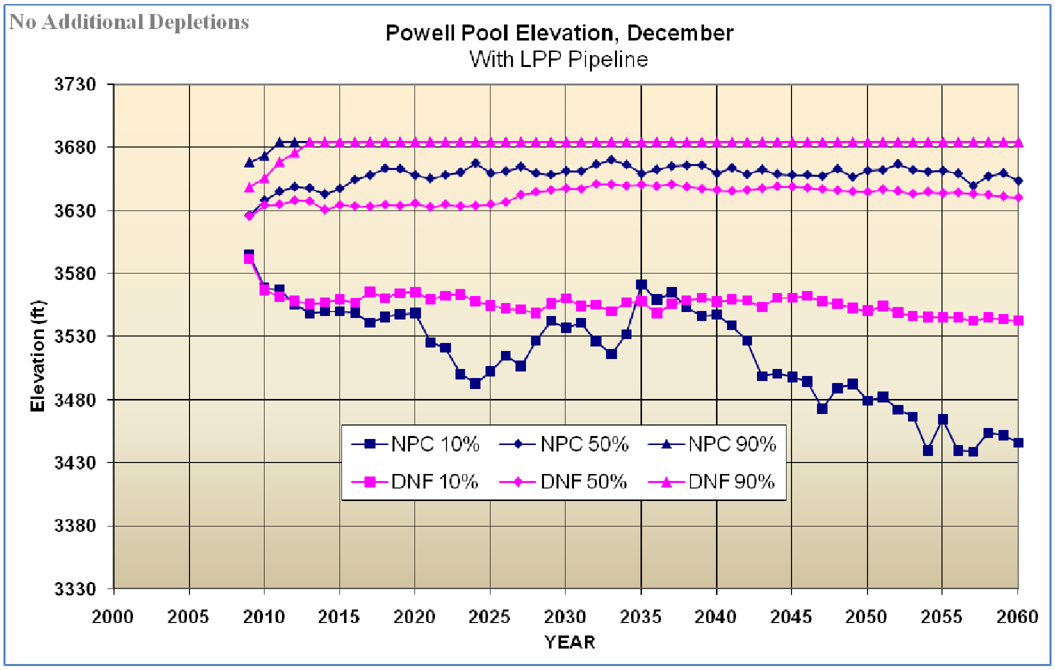
- Nonparametric Paleo-conditioned (NPC) Inflows – Developed from tree-ring data dating back to 762. The technique generates flows with the same magnitudes as the historic record but with more variety in the sequencing of wet and dry periods. NPC results in 125 simulated outcomes for each month, which are summarized using non-parametric statistics including the 10^{th}, 50^{th}, and 90^{th} percentiles. This technique generates flows with the same magnitudes as the historic record but with more variety in the sequencing of wet and dry spells. This inflow dataset and methodology was used for the sensitivity analysis in Appendix N of the 2007 Shortage EIS.

The Lake Powell Pipeline Hydrologic Modeling- No Additional Depletions Sensitivity Analysis report (Reclamation 2009b) compared scenarios with and without the LPP for each of the above mentioned hydrologic scenarios. A summary of the results outlined in the No Additional Depletions Sensitivity Analysis can be found in the LPP Surface Water Report (MWH 2011). This evaluation compares the two hydrologic input scenarios for the with-pipeline scenario. Thus, a comparison can be made between the observed hydrologic record (DNF) and the alternate paleo-conditioned inflows (NPC).

4.2 Lake Powell Pool Elevation

Figure 4-1 shows the differences in Lake Powell pool elevation in December at the 10^{th}, 50^{th}, and 90^{th} percentiles between the DNF and NPC hydrologic inflows for the with-pipeline depletion scenario. The NPC inflows produce a richer variety of wet and dry spells, resulting in different future elevations at Lake Powell when compared with the DNF inflow scenario.

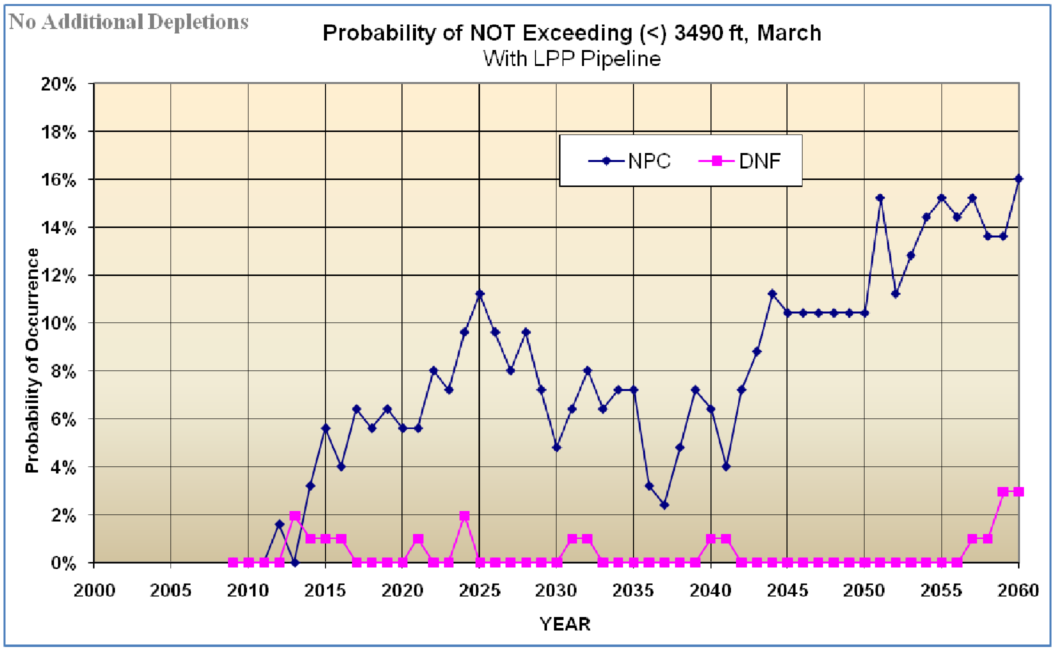
At the 50^{th} percentile, pool elevations could be up to 34 ft higher with the NPC inflow hydrology. The lowest simulated Lake Powell pool elevation dropped to 3,439 ft in the 10^{th} percentile for NPC flows as compared to 3,542 feet MSL for the 10^{th} percentile DNF flows, well above the 3,375 feet MSL minimum proposed intake elevation for the Lake Powell Pipeline. Lake Powell's minimum power pool elevation of 3,490 feet MSL would be reached by 2047 under the 10^{th} percentile.



Source: Reclamation (2009b)

Figure 4-1
Lake Powell Pool Elevation, December

The probability of not exceeding Lake Powell's minimum power pool (3,490 feet MSL) in the month of March was also analyzed. Figure 4-2 shows the probability of not exceeding Lake Powell's minimum power pool in March is higher with the NPC inflow scenario compared to the DNF inflow scenario. There are only a few years with less than four percent probability of not exceeding the minimum power pool elevation with the DNF inflow data. With the NPC inflow, all but four simulated years show a probability of not exceeding the minimum elevation. The greatest probability is 16 percent.

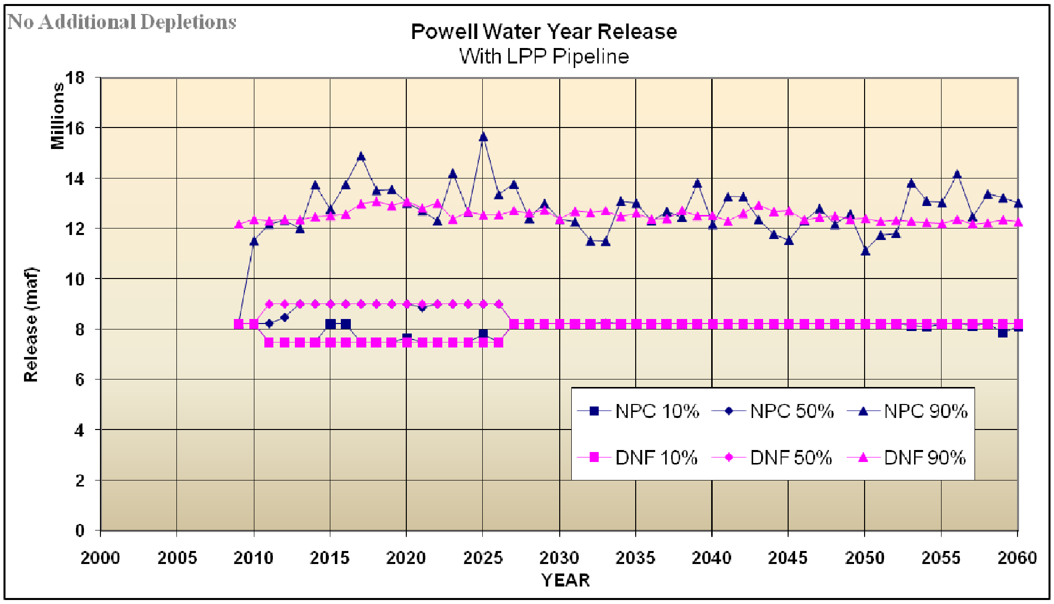


Source: Reclamation 2009b

Figure 4-2
Probability of Not Exceeding Minimum Power Pool Elevation in March

4.3 Lake Powell Releases

Figure 4-3 presents releases from Lake Powell by water year for the DNF and NPC scenarios. For the 10th and 50th percentiles, differences between the two hydrologic datasets would be minimal. For the 90th percentile, some years reflect larger releases for the NPC dataset and some years reflect smaller releases. The largest difference for a single water year is a 3.1 MAF increase under the NPC scenario.



Source: Reclamation 2009b

Figure 4-3
Lake Powell Releases by Water Year

4.4 CRSS Model Summary

In general, scenarios run with the Nonparametric Paleo-Conditioned inflows show a chance of slightly higher pool elevations at the 50th percentile and lower pool elevations at the 10th percentile. There is greater probability that the minimum power pool would not be exceeded (lower storage) with the NPC flows. Finally, there is a greater probability that more releases would be required from Lake Powell with the NPC flows. Differences fluctuate between simulated hydrologic year and percentile evaluated. A definitive conclusion regarding water availability in Lake Powell cannot be reached because the results depend upon the percentile evaluated. Overall, one can infer from these results that a greater variety of wet and dry spells, such as seen in the hydrology associated with tree-ring data reconstructions and as such could occur under future climate change conditions, would result in a greater variety of storage levels in Lake Powell and an increased likelihood of very low storage (below power pool elevation). However, Lake Powell pool elevations are never simulated by Reclamation to fall below the LPP intake operating elevation of 3,400 feet MSL. The physical ability to take deliveries into the LPP intake should not be jeopardized because the proposed intake elevation would be designed at 3,375 feet MSL elevation.

Chapter 5
Summary and Conclusions

Several studies relating climate change to runoff in the Colorado River Basin were reviewed. Based on these studies and the latest published synopsis of recent work, global climate models are showing average temperature increases of approximately 2° C, which imply runoff at Lees Ferry could decline between 4 and 18 percent by 2050 (Hoerling, et al 2009). Most studies that evaluate system responses to climate induced runoff reductions focus on a 10 percent and 20 percent reduction in flows with no change in precipitation. If only the current shortage management strategies outlined in the Colorado River Interim Guidelines for Lower Basin Shortages EIS (Reclamation 2007) are adhered to, a 10 percent reduction in runoff results in a 26 percent chance that Lake Powell would go dry (reservoir storage completely depleted) at least once by 2056 as compared to a 7.5 percent chance with no runoff reductions (Rajagopalan, et al 2009). If storage were "completely depleted", in the sense of this study, the Lake Powell pool elevation would be below the LPP intake elevation of 3,375 feet MSL. There is also potential for frequent shortages of 1-million acre-feet (MAF) by 2060 under these conditions (Barnett and Pierce 2009). The Rajagopalan study shows that under a 20 percent flow reduction and current shortage management strategies, the probability of storage depletion by 2056 is 51 percent (Rajagopalan, et al 2009). Barnett and Pierce 2009 show shortages of 2 MAF/year occurring 70 to 95 percent of the time by 2060 under a 20 percent reduction in flow scenario. These values are about 1.5- to 3-times the maximum lower basin delivery cut explicitly included in the preferred alternative plan of the Interim Guidelines EIS (Reclamation 2007).

The current guidelines for Lower Basin Shortages and operations of Lake Powell and Lake Mead impose shortages on the Lower Basin states based on storage elevations of Lake Mead. Proposed operations of Lake Powell were designed to avoid curtailment of Upper Basin users and to minimize the shortages in the Lower Basin. Based on the literature review, mean annual temperatures in the west may increase by at least 2^{o}C because of climate change. This temperature increase may reduce runoff by 2060, which in turn could affect storage in Lake Powell during the LPP project study period. The Colorado River Compact provides an allotment of 1.73 MAF per year to the State of Utah; however, Utah has already reduced its operating assumption of Colorado River yield by approximately 20 percent to about 1.4 MAF per year. Additional potential future curtailments could affect deliveries through the Lake Powell Pipeline, although the intake elevation of the pipeline is low enough to physically receive water from the reservoir under the most dire storage scenario. As noted in the Rajagopalan and the Barnett and Pierce studies, changes in management practices would certainly occur before Lake Powell would dry up. Rajagopalan suggests that aggressive shortage and demand management could reduce the risk. Other effective management strategies could include a program of water reuse, conservation, transfers between users, or other measures (Barnett and Pierce 2009, NAS 2007). The extent to which the LPP project would be affected would depend on the management strategies adopted.

In the event of shortages resulting from future climate changes, the Secretary of the Interior would operate the Colorado River to manage the supply for the benefit of water users and to meet obligations detailed in the Interim Guidelines EIS (Reclamation 2007). Water deliveries would be curtailed by each state under an average of shortages. The effects of shortages on water users within each state would be a state engineer responsibility.

The LPP study area portion of the Virgin River Basin is located in the upper-most part of Reclamation's Lower Basin region. The predicted 2050 to 2079 mean temperature for this area is 2.5 to 2.7^{o}C (4.5 to 5^{o} F) warmer than the 1950 to 1979 historical mean (Reclamation 2009a). This is similar to that in the Upper Colorado Basin. It is likely that runoff would be reduced for this basin as it is for the Upper Colorado

Basin. However, no studies specific to potential future climate induced runoff changes have been performed for the Virgin River Basin and specific predictions regarding the amount of runoff reduction anticipated in the Virgin River Basin have not been made. If runoff predictions made in the Upper Colorado River Basin were similar to those of the Virgin River Basin, a 10 to 20 percent decrease in future runoff may be possible. A 10 percent decrease in average annual flow in the Virgin River at Virgin could equate to approximately 13,200 acre-feet per year and a 20 percent decrease would be 26,400 acre-feet per year. This could significantly reduce yields of Quail Creek Reservoir and Sand Hollow Reservoir, which are filled from the Virgin River and supply substantial portions of the WCWCD water supply. Similar effects could be seen in streams in Cedar Valley.

In conclusion, inflow to Lake Powell is likely to decline in the future, either because of predicted climate change or to natural reversion toward the long-term historical mean determined from the tree-ring studies. Streamflow in the Virgin River is likely to decline, yet to what extent is unknown. Reduced inflow to Lake Powell could have detrimental effects on storage levels if stringent shortage and demand management strategies are not implemented. It is unknown at this time what impacts such management strategies might have on the State of Utah or the LPP project. The LPP intake would be designed at an elevation which would be physically capable of receiving water in times of low storage. There are currently no plans to curtail Upper Basin States' water use beyond what is required by the Colorado River Compact.

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Abbreviations and Acronyms

Abbreviation/Acronym	Meaning/Description
AWWA	American Water Works Association
Basin	Colorado River Basin
CG	Citizen's Guide to Colorado Climate Change
CICWCD	Central Iron County Water Conservancy District
Commission	Federal Energy Regulatory Commission
CRRM	Colorado River Reservoir Model
CRSS	Colorado River Simulation System
CRWAS	Colorado River Water Availability Study
DNF	Direct Natural Flow
DP	Direct Paleo
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
GCM	Global Circulation Models
HS	Hydro System
IPCC	Intergovernmental Panel on Climate Change
ISM	Index Sequential Method
JFRCCVS	Joint Front Range Climate Change Vulnerability Study
KCWCD	Kane County Water Conservancy District
LPP	Lake Powell Pipeline
LTRR	Laboratory of Tree-Ring Research
M&I	Municipal and Industrial
MAF	million acre-feet
MSL	Mean Sea Level
MWH	Montgomery Watson Harza
NAS	National Academy of Sciences
NPC	nonparametric paleo-conditioning
NWSRFS	National Weather Service River Forecasting System
PCM	Parallel Climate Model
PDSI	Palmer Drought Severity Index
PNAS	Proceedings of the National Academy of Sciences
Reclamation	U.S. Bureau of Reclamation
UDWR	Utah Department of Water Resources
VIC	Variable Infiltration Capacity
WCWCD	Washington County Water Conservancy District
WEAP	Water Evaluation and Planning
WWA	Western Water Assessment

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