Hasenbeck, Eleanor. Sept. 5, 2018.

Yampa River is placed on call for 1st time ever

News | September 5, 2018

Eleanor C. Hasenbeck
ehasenbeck@SteamboatPilot.com

The Yampa River flows through Dinosaur National Monument around Aug. 18. Low flows in the lower stretch of the river led water managers to curtail some use of water from the river. (courtesy photo)

STEAMBOAT SPRINGS — For the first time, water users on the main stem of the Yampa River have been curtailed.

Due to low water conditions in the lower stretch of the river near Dinosaur National Monument, the Colorado Division of Water Resources placed a call on the river Tuesday. The call applies to water users upstream from the river's lowest diversion point, which essentially places the entire river on call.

"We are now faced again with the Yampa River being extremely low at its lower end, and we are unable to both protect the Endangered Fishes Recovery Program reservoir water and allow all water users to continue to divert water," Erin Light, the area division engineer, wrote in an email to water users in the Yampa River Basin on Wednesday morning.

The Division of Water Resources places a call on a stream when water rights owners do not receive the amount of water they have a legal right to. When a call is in place, some water users are forced to reduce or stop their use in order to send enough water downstream to fulfill the older water right.

A call was placed on the river on Aug. 22, but its implementation was delayed.

"A lot of water users are being affected," Light said. "There are certain drainages where water users don't have any measuring device at all, and that's what we started shutting off (Tuesday)."

Hasenbeck, Eleanor. Sept. 5, 2018.

By the numbers

Yampa River flows at noon Wednesday, Sept. 5:
Steamboat Springs: 62.3 cubic feet per second
Above Elkhead Creek near Hayden: 61.3 cfs
Below Craig: 114 cfs
Near Maybell: 61.4 cfs
Deerlodge Park: 19.3 cfs

These users — the ones who aren't measuring how much water they're diverting — were the first to be shut off. On the main stem of the river, these devices are required to ensure that released reservoir water makes it to the user who purchased it.

"Personally, I believe it's a good thing," said Doug Monger of the call. "Well, I wouldn't say it's a good thing. It's a day of reckoning."

Monger is a Routt County commissioner and the county's representative on the Colorado River District board of directors.

"We need to get into the current century somehow," Monger said. "Heck, we haven't had measuring devices on our ditches. It's a free river. You just use all you want. There's a whole new accountability coming down with the drought and the 19-year lowest cycle of (the Colorado) River right now."

Monger said right now the Colorado River has the lowest amount of water flowing downstream in recorded history.

Low water in the Colorado is important to water managers in the Yampa River Basin because the Yampa is one of the Colorado River's major tributaries. This year, about 52 percent of the water flowing out of the state of Colorado into Lake Powell came from the Yampa, White and Green river basins.

On a 10-year rolling acreage, the state of Colorado must send a set amount of water to Lake Powell for use by Arizona, California, Nevada and portions of Utah and New Mexico under the Colorado River Compact of 1922. If Colorado does not meet its obligation, a compact call would be administered.

No precedent exists for a compact call, so it is unclear how water managers would decide whose water would be curtailed statewide.

On the Yampa, any user who has a water right decreed after Sept. 16, 1951, will be curtailed. Light said it is likely the Division of Water Resources will change this to an earlier date depending on river conditions.

Water users on the Yampa's tributaries who do not have a measuring device and proper head gate — the gate that regulates the flow of water entering an irrigation system — will be shut off, regardless of how old their water right is. All water users who do not have a formal court-decreed water right will also be curtailed.

Water commissioners are currently visiting head gates to determine if water users can divert water. Those that have water rights filed after the priority date and those that don't have a measuring device will be shut and tagged with a notice explaining the situation to the water rights holder.

Some of the city of Steamboat Springs' water rights will be shut off. City water customers will not notice a change in service, as the city will purchase reservoir water from Stagecoach Reservoir to augment water from the Yampa.

"Fortunately, the city has planned for this day, and we have an augmentation plan in place," said Kelly Romero-Heaney, water resources manager for Steamboat Springs. "We've arranged our water rights portfolio, so that we'll be able to continue to use water to supply our customers and irrigate our parks."

Both Hayden and Craig have older water rights and likely will not see curtailment, Light said. Tri-State Generation and Transmission will pay to release water to keep up energy generation at Craig Station with releases from Elkhead and Stagecoach reservoirs.

"Just because one has a water right, doesn't mean that there's necessarily water available for that right," Romero-Heaney said. "The river has never operated in a way to account for that, so we'll learn a lot about all of our water rights portfolios after this year."

Light said much of the water that's being diverted is being put to use to water fall pastures for cattle and sheep. Flows could improve as some water users decide to stop irrigating for the year, she said.

Rainfall could help put more flows in the river, she added, and cool temperatures could slow down plants' consumption of Yampa water.

"When we see the willows and everything start to die off for the year, you will notice we see more water in the river," Light said.

These conditions could allow the Division of Water Resources to lift the call or allow users with newer water rights to divert water.

"There's a whole new responsibility for everybody, including the ranchers, including households, golf courses, municipalities, consumers," Monger said. "Everybody needs to do a better job doing what we're doing, and there's going to be an uptick in accountability of it."

Hasenbeck, Eleanor. Sept. 5, 2018.

To reach Eleanor Hasenbeck, call 970-871-4210, email ehasenbeck@SteamboatPilot.com or follow her on Twitter @elHasenbeck.

Drought plan aims to curtail water loss at Lake Powell, Lake Mead

Avoiding serious shortages at Lake Powell, Lake Mead is the goal

By Jonathan Romeo Herald staff writer
Friday, Oct. 12, 2018 1:00 PM
Updated: Friday, Oct. 12, 2018 7:49 PM

https://the-journal.com/articles/113368-drought-plan-aims-to-curtail-water-loss-at-lake-powell-lake-mead

Water managers in Southwest Colorado voiced grave concerns Wednesday that communities along the Front Range should contribute just as much as the Western Slope in addressing dwindling water reserves in Lake Powell and Lake Mead.

“We don’t think that should be on the backs of West Slope communities and West Slope agriculture,” said Bruce Whitehead, executive director of Southwestern Water Conservation District.

The Colorado River supports about 40 million people and 5.5 million acres of farmland in seven western states, divided into the Upper Basin (Colorado, New Mexico, Utah, Wyoming) and the Lower Basin (Arizona, California, Nevada).

But prolonged drought and increasing demand are causing those states to draft a new plan about how that water is divided.

Lain Leoniak, assistant attorney general for the state of Colorado, said previous water agreements were based on data gathered during abnormally wet years in the 1900s, which led to overestimations of available water.

Water compacts agreed upon in 1922 and 1948 were renegotiated in 2007, but even so, worsening drought conditions and overuse of water created the need for a new water agreement and an emergency drought plan.

A draft of the “Upper Colorado River Basin Drought Contingency Plan” was released Tuesday and discussed Wednesday at the Southwest Basin Roundtable at the Durango Public Library.

The drought plan is the result of almost two decades of prolonged drought throughout the region that has changed reasonable expectations about how much water there is to use and deliver.

Four of the five lowest years on record occurred in the past 18 years, Leoniak said. Seven of the last 18 years of inflows into Lake Powell were less than 5 million acre-feet. The years 2002 and 2018 are the first and second driest years on record.

Now, Lake Powell is less than half full. If water levels continue to drop at Lake Powell and Lake Mead, it could have serious implications for how water rights are distributed in the Colorado River Basin.

Lake Powell is less than half full. If water levels continue to drop at Lake Powell and Lake Mead, it could have serious implications for how water rights are distributed in the Colorado River Basin.
Associated Press file

About three years ago, the Lower Basin states implemented a drought contingency plan, which calls for cutbacks on water use and for conservation measures.

Leoniak said the Upper Basin states have never come close to falling out of compact compliance, which says the Upper Basin will not cause the flow at Lee’s Ferry in Arizona to fall below 75 million acre-feet over a 10-year span.

In fact, the Upper Basin states have delivered 91 million-acre feet over the past 10 years, Leoniak said.

“But ... we’ve had 18 years of very dry hydrology, so we need to be responsible water managers and plan,” she said. “Whether we ever implement the plan is a different story, but we need to plan.”

John Currier, chief engineer of the Colorado River Water Conservation District, said another major concern is having Lake Powell fall below a critical water level that would no longer allow the dam to pump for hydroelectric power.

That could affect rural communities that depend on the electricity, as well as cut off revenue that is used for water treatment and endangered species programs. And, of course, it could lead to Upper Basin states not meeting their water compact.

Brent Newman with the Colorado Water Conservation Board said the drought contingency plan in the works aims to avert this worst-case scenario.

For starters, Upper Basin states could implement smaller-scale measures, like using weather modification programs, such as cloud seeding, and removing plants that absorb a significant amount of water, Newman said.

The plan would also move water into Lake Powell from Upper Basin state reservoirs, such as Flaming Gorge in Wyoming, Blue Mesa Reservoir in Colorado and Navajo Reservoir along the Colorado-New Mexico border.

But if these measures fall short, water managers must consider the less preferred and far more controversial prospect of “demand management,” which the Colorado Water Conservation Board hopes would be “temporary, voluntary and compensated.”

Members of the Southwest Basin Roundtable made clear to state water managers that communities along the Front Range, which relies on transmountain diversions from the Western Slope, should also implement water-saving measures.
Jerry McBride/Durango Herald file
Because the demand management program is more controversial, it is being considered separately from the drought contingency plan, Newman said. Both processes he said would be “heavily vetted” by Colorado communities.

“It would not be done in a vacuum,” he said.

Leoniak said, ultimately, the drought contingency plan would function as a Band-Aid until the wider water agreement is renegotiated. Any plans would need unanimous agreement among the four Upper Basin states.

Members of the Southwest Basin Roundtable made clear to state water managers that communities along the Front Range, which relies on transmountain diversions from the Western Slope, should also implement water-saving measures.

“Contributions should be roughly equal on the East Slope as the West Slope,” Whitehead said.

Mike Preston, general manager of the Dolores Water Conservancy District and chairman of the Southwest Basin Roundtable, said a subgroup of the roundtable would be formed to dive deeper into the issues of the drought plan.

jromeo@durangoherald.com

James, Ian. Dec. 14, 2019. Arizona Republic.

Feds will review Colorado River rules, Interior boss says, with an eye on long-term risks

Ian James, Arizona Republic Published 11:57 a.m. MT Dec. 14, 2019

LAS VEGAS — Federal water managers are about to start reexamining a 12-year-old agreement among Western states that laid down rules for dealing with potential water shortages along the Colorado River.

Interior Secretary David Bernhardt said he asked the Bureau of Reclamation to start the review at the beginning of 2020, rather than by the end of 2020, which is the deadline under the existing agreement.

The bureau's officials will examine how the 2007 guidelines have worked as the agency prepares for negotiations among the seven states on a new set of rules that will take effect after 2026.

"It makes sense to review how well something worked before determining its replacement," Bernhardt said Friday during a speech at a Colorado River conference in Las Vegas. "We think that starting now and not waiting until the deadline a year from now makes sense."

During the review, he said, federal water managers who operate dams on the river want input from the states, tribes, non-governmental organizations, and the public. They plan to finish a report by the end of next year.

The Trump administration will reexamine the long-term rules, which dictate water cutbacks during shortages, just as a separate seven-year deal kicks in next year to prevent the river's depleted reservoirs from falling to critically low levels.

Multi-state plan set to take effect

The levels of Lake Powell and Lake Mead have dropped dramatically since 2000. The river has long been overallocated, and successive dry years have taken a toll. Scientists have found that climate change, by cranking up temperatures, has further contributed to declines in the river's flow during the past two decades.

Lake Powell now sits 52% full, and Lake Mead is 40% full.

In an attempt to reduce the risks of the reservoirs falling into severe shortages, the seven states in the Colorado River Basin last year reached a set of agreements. Arizona and Nevada will start taking less water from the Colorado River in January under a deal with California called the Lower Basin Drought Contingency Plan, or DCP, which the states' representatives signed at Hoover Dam in May (/story/news/local/arizona-environment/2019/05/20/drought-contingency-plan-done-now-what/3477317002/).

Cal ... voir levels continue to fall. And Mexico agreed under a separate accord to start cor ... ir near Las Vegas.

WATER CUTBACKS: Set to begin under deal to 'buy down risk' on Colorado River (/story/news/local/arizona-environment/2019/12/10/arizona-nevada-mexico-colorado-river-drought-climate/4359571002/)

These agreements, along with a separate deal among four states in the river's Upper Basin, are designed to boost the water-starved reservoirs through 2026, when the next set of long-term rules are due to take effect.

Bernhardt said finishing the agreements last year was a great accomplishment, and he credited representatives of the states, water districts and tribes. He said the agreements will "incentivize conservation and share the burdens should drought and low runoff conditions persist."

Climate change, energy development

He didn't mention the words climate change during his speech at the conference. But during a press conference afterward, reporters asked Bernhardt about the role of climate change.

"I certainly believe the climate is changing," Bernhardt said. "I spend a lot of time with our scientists, and I spend a lot of time with our models. And you know, what the scientists tell me is that the best thing we can do is make sure that if we're using a model, we use multiple models and multiple ranges within each model. And so that's what I've insisted on when we're looking forward to the future."

In projecting the river's flows into the future, he said, "we absolutely follow best practices all the time."

Interior Secretary David Bernhardt listens to a reporter's question at the Colorado River Water Users Association conference in Las Vegas. *(Photo: Ian James/The Arizona Republic)*

President Donald Trump's administration has begun pulling out of the landmark Paris climate agreement (/story/news/politics/2019/11/04/paris-climate-deal-mike-pompeo-submits-formal-notice-us-withdrawal/4159493002/), and has promoted oil and gas drilling.

In California, the Trump administration is moving forward with a plan that could open up about 1.2 million acres (/story/news/politics/2019/11/08/trump-administration-drilling-in-california-near-yosemite-sequoia/2509567001/) to new oil and gas drilling. When asked about environmental groups' opposition to the plan, Bernhardt said: "We have really strong policy guidance and laws that say that we're supposed to develop energy, and we will develop energy responsibly."

Be ... byist for the oil and gas industry in the West.

James, Ian. Dec. 14, 2019. Arizona Republic.

“The president was very clear when he ran for office on his position on energy. He's for an all-of-the-above approach,” Bernhardt said. He pointed out that oil development on federal lands has generated revenues in New Mexico for schools and other state programs.

“And so, when people tell me that they want to stop oil and gas development on federal lands, I say call the governor of New Mexico,” Bernhardt said.

A 'disconnect' in Trump policies

John Fleck, director of the University of New Mexico’s Water Resources Program, said Bernhardt’s comments reflect a dichotomy within the federal government in which officials are taking steps on climate adaptation but not on combating planet-warming emissions.

On the one hand, water managers at the Bureau of Reclamation are working with scientists and using climate models to assess risks and project the river flows into the future, Fleck said.

“They’re absolutely taking climate change seriously. It’s built into the modeling work they’re doing,” Fleck said. “You don’t find water managers doubting the reality of human-caused climate change and its effects. They’re seeing it in the flow in their systems, and they’re dealing with it.”

On the other hand, he said, there is a “disconnect” in that the Trump administration isn’t taking steps to reduce greenhouse gas emissions.

“So that increases our risk,” Fleck said. “That’s a problem because we need to reduce greenhouse gases to mitigate the effects on the Colorado River.”

One of Lake Mead's spillways sits empty. The last time water lapped at the top of the spillway was 1999. The reservoir has fallen during a nearly 20-year run of mostly dry years. *(Photo: Ian James/The Arizona Republic)*

The Colorado River and its tributaries provide water for about 40 million people and more than 5 million acres of farmland from Wyoming to Southern California.

The river has dwindled during a nearly 20-year run of mostly dry years, and research has shown that rising temperatures are affecting the river.

Researchers have found that about half the trend of decreasing runoff (/story/news/local/arizona-environment/2018/09/07/rising-temperatures-flow-colorado-river-climate-change-warming/1212535002/) from 2000-2014 in the Upper Colorado River Basin was the result of unprecedented warming. Higher temperatures have reduced the flow of streams and increased the amount of water that evaporates off the landscape.

In one study (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016WR019638), climate scientists Brad Udall and Jonathan Overpeck used climate models to estimate a business-as-usual scenario of greenhouse gas emissions. They projected that without changes in precipitation, warming will likely cause the Colorado River’s flow to decrease by 35% or more by the end of the century.

SPECIAL REPORT: Megafarms with deep wells are draining the water beneath rural Arizona (https://www.azcentral.com/in-depth/news/local/arizona-environment/2019/12/05/unregulated-pumping-arizona-groundwater-dry-wells/2425078001/)

Ma ... nents a “bridge solution” or a temporary fix for the Colorado River. They say the deal wil ... hing while allowing time to plan bigger steps.

Talks on the deal lasted four years, and the next round of negotiations could turn out to be more difficult.

James, Ian. Dec. 14, 2019. Arizona Republic.

Bernhardt said the government's review will focus on "what's worked, what's not worked." He said that will include looking at lessons as the water cutbacks kick in next year under the drought deal.

Be nges, he is optimistic that parties across the region will continue working together to sol

"We have a legacy here of states cooperating in a way that is absolutely incredible," he said.

James, Ian. Dec. 14, 2019. Arizona Republic.

Reach reporter Ian James at ian.james@arizonarepublic.com (mailto:ian.james@arizonarepublic.com) or 602-444-8246. Follow him on Twitter: @ByIanJames (https://twitter.com/ByIanJames)

Environmental coverage on azcentral.com and in The Arizona Republic is supported by a grant from the Nina Mason Pulliam Charitable Trust. Follow The Republic's environmental reporting team at environment.azcentral.com (https://www.azcentral.com/local/environment/) and @azcenvironment on Facebook, Twitter (https://twitter.com/azcenvironment) and Instagram (https://www.instagram.com/azcenvironment/).

Read or Share this story: https://www.azcentral.com/story/news/local/arizona-environment/2019/12/14/federal-government-review-colorado-river-rules-2020/2641339001/

HYDROLOGIC DETERMINATION
2007

Water Availability from Navajo Reservoir and the Upper Colorado River Basin for Use in New Mexico

April 2007

MAY 23 2007

Date

Secretary of the Interior

I. Executive Summary

Determination as to the availability of water under long-term service contracts for uses from Navajo Reservoir involves a projection into the future of estimated water uses and water supplies. On the basis of this hydrologic investigation, water depletions by the Upper Basin states from the Upper Colorado River Basin can be reasonably allowed to rise to an annual average of 5.76 million acre-feet (maf) per year, exclusive of Colorado River Storage Project (CRSP) reservoir evaporation from Lake Powell, Flaming Gorge Reservoir, and the Aspinall Unit. This depletion level can be achieved under the same shortage criteria upon which the allowable Upper Basin yield was determined in the 1988 Hydrologic Determination.

This document determines the availability through at least 2060 of water from New Mexico's Upper Basin allocation and Navajo Reservoir to service a proposed contract for the Navajo Nation's consumptive uses in New Mexico under the Navajo-Gallup Water Supply Project in the annual amount of 20,780 acre-feet (af) and the Navajo Indian Irrigation Project (NIIP) in the amount of 270,000 af per year on average over any period of ten consecutive years. It also is likely that sufficient water will be available from Navajo Reservoir to service the proposed contract after the 2060 planning horizon, depending upon future storage, hydrologic conditions, and other factors. This determination does not guarantee that the United States will be able to deliver water under the proposed contract without shortages in deliveries, and does not obligate the United States to maintain storage facilities beyond their useful lives. The proposed contract is part of a Navajo Nation water rights settlement in the Upper Basin in New Mexico, and the settlement provides that uses made pursuant to the contract will be subject to administration in accordance with the Upper Colorado River Basin Compact and New Mexico state law. Implementation of the Navajo-Gallup Water Supply Project and the NIIP is subject to compliance with federal environmental laws including the National Environmental Policy Act and the Endangered Species Act.

II. Introduction

The State of New Mexico has proposed the Navajo-Gallup Water Supply Project to provide a renewable water supply from the San Juan River for municipal and domestic uses for Indian and non-Indian communities located within New Mexico. Uses under the project by the Jicarilla Apache Nation and the City of Gallup would be supplied through the Jicarilla Apache Nation's Navajo Reservoir water supply contract approved by Congress in 1992. Uses in New Mexico under the project by the Navajo Nation would be supplied through a proposed new Navajo Reservoir water supply contract that is a component of the San Juan River Basin in New Mexico Navajo Nation Water Rights Settlement Agreement (hereinafter referred to as the Settlement Agreement) that the State of New Mexico and the Navajo Nation executed on April 19, 2005. The new contract also would supersede the existing Navajo Reservoir water supply contract for the NIIP.

On June 19, 2003, the Upper Colorado River Commission resolved that the States of the Upper Division consent to the Navajo-Gallup Water Supply Project, provided that water diverted by the project for use in New Mexico shall be a part of the consumptive use apportionment made to the State of New Mexico by Article III(a) of the Upper Colorado River Basin Compact. The maximum amount of consumptive use through the project by the Navajo Nation in New Mexico that would be permitted in any one year under the Settlement Agreement and the proposed contract is 20,780 acre-feet.

Public Law 87-483 at section 11(a) requires that no long-term contract, except contracts for the NIIP and the San Juan-Chama Project, shall be entered into for the delivery of water stored in Navajo Reservoir, or any other waters of the San Juan River and its tributaries to which the United States is entitled, until the Secretary of the Interior has determined by hydrologic investigation that sufficient water to fulfill such contract is reasonably likely to be available for use in the State of New Mexico under the allocations made in Articles III and XIV of the Upper Colorado River Basin Compact, has submitted such determination to Congress, and Congress has approved the contract. The last such hydrologic determination was approved by the Secretary on February 2, 1989 (Hydrologic Determination, 1988, Water Availability from Navajo Reservoir and the Upper Colorado River Basin for Use in New Mexico, hereinafter referred to as the 1988 Hydrologic Determination). The 1988 Hydrologic Determination evaluated the availability of water from the Navajo Reservoir water supply for the Jicarilla Apache Nation's Navajo Reservoir water supply contract. The State of New Mexico, by letter dated May 3, 2005, requested that the 1988 Hydrologic Determination be updated to evaluate the availability of water to service the proposed Navajo-Gallup Water Supply Project.

This hydrologic investigation is made for the purpose of contracting for water from the Navajo Reservoir water supply for the Navajo Nation's uses in New Mexico under the Navajo-Gallup Water Supply Project. The Bureau of Reclamation prepared this hydrologic investigation in consultation with the Upper Colorado River Commission because of the critical nature of this determination of the Upper Basin water supply. The Upper Colorado River Basin Compact created and defined several areas of responsibility for the Commission that directly and indirectly relate to this investigation.

III. Upper Basin Yield

A. General Upper Basin Hydrology

Based on the Bureau of Reclamation's Colorado River Simulation System (CRSS), natural flows for the period 1906-2000, the natural runoff from the Upper Colorado River Basin averages about 15.3 maf per year at Lee Ferry. Of this amount, approximately 2 maf per year originates in the San Juan River Basin above Bluff, Utah. New Mexico can only develop its Upper Basin allocation from the San Juan River and its tributaries. The Bureau of Reclamation's Colorado River System Consumptive Uses and Losses Report for 1996-2000 indicates that current consumptive uses from the San Juan River Basin average about 382,400 af per year in New Mexico and about 192,500 af per year in Colorado. Only minor amounts of depletions are made in the San Juan River Basin in Utah and Arizona.

B. Approach

This hydrologic investigation considers and uses many of the same basic assumptions as the 1988 Hydrologic Determination. Both investigations assume use of the CRSS natural flows at Lee Ferry, minimum releases from Lake Powell of between 7.48 maf and 8.23 maf annually, an allowable overall shortage of no more than 6 percent for a critical period, either maintenance or use of the minimum power pools at CRSP units, reduced storage capacity in Lake Powell due to sedimentation, and inclusion of bank storage. The CRSS natural flows at Lee Ferry for the period 1971-1980 were increased to reflect recalculation of historic irrigation depletions in the Upper Basin using the Soil Conservation Service (SCS) modified Blaney-Criddle method with SCS effective precipitation. The revised CRSS natural flows for 1971-1980 are consistent with the CRSS natural flows at Lee Ferry determined for the remainder of the 1906-2000 period of record. Also, sedimentation in Lake Powell was adjusted to reflect a 2060 planning horizon, and a 4 percent bank storage factor was used in this investigation consistent with Reclamation's current CRSS model.

Neither the Lower Division states nor the Upper Colorado River Commission agree with the modeling assumption for the objective minimum release used in this report. At the request of the Commission, this hydrologic investigation considers for planning purposes both the objective minimum release of 8.23 maf and a minimum release from Lake Powell of 7.48 maf annually. However, this hydrologic determination does not quantify the Colorado River Compact Article III(c) requirement or make or rely on a critical compact interpretation regarding Article III(c). The 1988 Hydrologic Determination also showed the Upper Basin yields under these minimum release scenarios.

Mass balance analyses were used to analyze potential water use by the Upper Basin under 2060 conditions. The mass balance considers Upper Basin reservoir storage, natural flows at Lee Ferry, deliveries to the Lower Basin, consumptive use demands in the Upper Basin, and CRSP evaporation as a function of storage volume. All existing Upper Basin storage capacity was included in the analysis because all storage supports water use in the Upper Basin and impacts stream flows. The CRSP and non-CRSP reservoirs as groups were assumed to be the same percent full each year, and CRSP storage was assumed to be distributed between units in accordance with the average historic storage distribution. The CRSP reservoir evaporation that is used in the mass balance analyses includes evaporation from Lake Powell, Flaming Gorge Reservoir, and the Aspinall Unit that is shared among the Upper Division States, but excludes evaporation from Navajo Reservoir which is chargeable to the states based on use. Shared CRSP reservoir evaporation is modeled using a regression equation relating historic shared CRSP reservoir evaporation from Lake Powell, Flaming Gorge Reservoir, and the Aspinall Unit to the aggregate historic storage volume in these reservoirs plus Navajo Reservoir. Evaporation equations were developed for both active and live storage, and were applied to estimate annual shared CRSP evaporation based upon yearly reservoir storage volume (surface area). The 1988 Hydrologic Determination considered variations in shared CRSP reservoir evaporation with storage for conducting statistical trace analyses to evaluate possible frequencies and magnitudes of shortages; however, it deducted a long-term average shared CRSP reservoir evaporation of 0.52 maf per year from the critical-period Upper Basin yield of at least 6.0 maf/yr to determine the amount of water available for Upper Basin uses through the critical period.

C. Results

Mass balance analyses were performed for various combinations of storage, Lower Basin deliveries, and overall shortages to evaluate the allocation of water to the Upper Basin (see mass balance analyses provided in Appendix A). The following is a summary of the results of the analyses:

Storage Assumption	Minimum Lower Basin Delivery (maf)	Yield without Shortages (maf)	Yield with 6% Overall Shortages (maf)
Maintain minimum power pools	8.25	5.55	5.79
	7.50	6.30	6.57
Use minimum power pools	8.25	5.72	5.98
	7.50	6.47	6.76

The yield for this analysis is defined as the amount of water available at Lee Ferry for use, on average, by the Upper Basin, exclusive of shared CRSP reservoir evaporation. Shortages in the above table are defined as 6 percent or less overall computed shortage for any period of 25 consecutive years consistent with the 1988 Hydrologic Determination. Results are shown for minimum Lower Basin deliveries of 8.25 maf and 7.50 maf as was done in the 1988 Hydrologic Determination. The analyses in this investigation should not be construed to prejudice the positions of either the Upper Colorado River Commission or the States of the Lower Division as to the interpretation or administration of Article III of the Colorado River Compact.

For those analyses that use an allowable or tolerable overall shortage of 6 percent or less of the use over any period of 25 consecutive years, the results indicate that there would be 5 years of shortage to meet all demands on the Upper Basin out of 95 years of record used in this investigation. However, the annual amounts of computed shortages for those five years would not fully materialize because Upper Basin consumptive uses will be below average under critical period hydrology due to physical water supply shortages at the sites of use in the Upper Basin. For example, the natural flow at Lee Ferry for 1977 was only 5.55 maf, and severe water supply shortages occurred throughout the Upper Basin in that year. The computations of shortage in this analysis give conservatively large estimates of annual shortages at Lee Ferry and do not fully reflect all factors, including physical shortages in the Upper Basin that might contribute or relate to a shortage condition at any given time. The computed shortages in this investigation do not equate to administrative calls to curtail Upper Basin uses.

D. Comparison to 1988 Hydrologic Determination

The 1988 Hydrologic Determination concluded that the total Upper Basin yield, including CRSP reservoir evaporation, is at least 6.0 maf per year for the 1953-1977 critical period hydrology with a 6 percent allowable overall shortage for the period. Under the conditions assumed in the current investigation, the shared CRSP evaporation varies with CRSP storage assumptions and storage levels. Assuming an average annual Upper Basin use of 5.79 maf, an annual Lower Basin delivery of 8.25 maf, and maintenance of the power pools, the shared CRSP evaporation would range from an average of about 0.25 maf per year over the worst 25-year period of reservoir storage draw down (1953-1977) to an average of about 0.49 maf per year over the period of record used in the analysis (1906-2000). Thus, the total Upper Basin depletion, including both Upper Basin uses and CRSP reservoir evaporation, would average about 6.04 maf per year or more over any period of 25 consecutive years. The total Upper Basin depletion amount for this scenario for the 1953-1977 period is comparable to the total Upper Basin depletion of 6.0 maf per year determined to be available for the period by the 1988 Hydrologic Determination. The difference is due to the revisions made to the CRSS natural flows for 1971-1980. If the minimum power pools are used, the shared CRSP reservoir evaporation is reduced due to increased reservoir storage draw downs.

IV. Water Use Projections

A. Upper Basin

The Upper Colorado River Commission last approved depletions schedules for the Upper Division States for planning purposes in 1999. The depletions schedules, dated January 2000, project that the total Upper Basin use exclusive of shared CRSP reservoir evaporation will average about 5.37 maf per year under 2060 development conditions. Unless additional Upper Basin water development occurs by 2060 as compared to the January 2000 depletions schedules, the Upper Basin use may average less than about 5.40 maf per year from now through 2060. The time required to develop the Upper Basin allocation reduces risk of shortage within the 2060 planning horizon.

B. State of New Mexico

For use in this investigation, the New Mexico Interstate Stream Commission provided the Bureau of Reclamation with a preliminary revised schedule of anticipated depletions through 2060 from the Upper Basin in New Mexico dated May 2006 (see Appendix B). The revised depletions schedule includes irrigation depletions calculated using the SCS modified Blaney-Criddle method with SCS effective precipitation so that demands and supply for this hydrologic investigation are evaluated using consistent methodologies.

The irrigation depletions for the Navajo Nation's irrigation projects are water right depletion amounts provided by the Settlement Agreement. Both this hydrologic investigation and the 1988 Hydrologic Determination assume use of the full depletion amount for the NIIP. This is a conservative assumption because the total NIIP depletion right is not expected to be fully utilized under normal farm management practices. The revised depletions schedule does not include New Mexico's allocation of shared CRSP reservoir evaporation. The revised New Mexico depletions schedule shows a total anticipated depletion of 642,000 af per year, on average, for uses in New Mexico under 2060 development conditions. This represents an increase in New Mexico's total Upper Basin depletion, excluding shared CRSP reservoir evaporation, of 23,000 af per year, or about 0.02 maf per year, as compared to the January 2000 depletions schedules.

V. Probabilities of Calls to Curtail Upper Basin Uses

The 1988 Hydrologic Determination included a probabilistic risk analysis of administrative calls to curtail Upper Basin uses that indicated that: (1) such calls would occur rarely at an Upper Basin demand level of 6.1 maf per year, though their effects could have significant impact to the Upper Basin; and (2) the frequency and magnitude of such calls would diminish rapidly below this demand level. The risk analysis was made using the CRSS model. It is not necessary for this investigation to duplicate such a risk analysis.

The computations of shortage in this current investigation give conservatively large estimates of annual shortages at Lee Ferry and do not fully reflect all factors, including physical shortages in the Upper Basin that might contribute or relate to a shortage condition at any given time. While this investigation uses a 2060 reservoir storage sedimentation condition for Lake Powell, a risk analysis should vary the storage development and sedimentation conditions over time. In addition, it will take decades to develop the Upper Basin allocation. Therefore, risk of shortage is reduced within a 2060 planning horizon. Even using the CRSS model, computed shortages would not necessarily equate to administrative calls to curtail Upper Basin uses.

VI. Physical Availability of Water from Navajo Reservoir

The Bureau of Reclamation, using a detailed hydrologic model for the San Juan River Basin, has evaluated the physical availability of water from Navajo Reservoir and the San Juan River for the Navajo-Gallup Water Supply Project, taking into account, among other things, the habitat needs of San Juan River populations of fish species listed as endangered under the Endangered Species Act. The physical water supply analysis contained in the Biological Assessment, Navajo-Gallup Water Supply Project, dated August 16, 2005, indicates that sufficient water is likely to be available from the Navajo Reservoir water supply for the Navajo Nation's uses under the project. Although the depletions for individual uses in New Mexico that were used in the Biological Assessment differ slightly from those in New Mexico's May 2006 revised depletions schedule, the physical water supply analysis in the Biological Assessment assumes up to about 640,500 af per year of depletion, on average, in New Mexico from the San Juan River. This amount of total average depletion in New Mexico is not significantly different than the amount of total average depletion in New Mexico shown in the May 2006 revised New Mexico depletions schedule under 2060 development conditions.

VII. Conclusions

It is concluded that based on the analysis performed by Reclamation in consultation with the Upper Colorado River Commission, the Upper Basin yield and New Mexico water allocation needed to support New Mexico's revised Upper Basin depletions schedule are reasonably likely to be available. The mass balance analyses results are sufficient to conclude that: (1) the Upper Basin yield is at least 5.76 maf per year, on average, excluding shared CRSP reservoir evaporation; (2) New Mexico's Upper Basin allocation is at least 642,400 af per year, excluding shared CRSP reservoir evaporation; and (3) the total anticipated average annual consumptive use in New Mexico from the Upper Basin, including Navajo Reservoir evaporation of 642,000 af per year as shown in the revised New Mexico depletions schedule is not likely to exceed New Mexico's Upper Basin allocation. This conclusion is reached assuming full use of the Navajo Nation's proposed depletion rights under the Settlement Agreement for both the Navajo-Gallup Water Supply Project and the NIIP.

Based upon this hydrologic investigation for a planning horizon through 2060, the May 2006 revised New Mexico depletions schedule, and the Biological Assessment for the Navajo-Gallup Water Supply Project, sufficient water is reasonably likely to be available from the Navajo Reservoir water supply through at least 2060 to fulfill the contract that is proposed by the Settlement Agreement to provide water for the Navajo Nation's uses in New Mexico under the Navajo-Gallup Water Supply Project and the NIIP. If the term of the contract extends beyond 2060, or is perpetual as proposed by the Settlement Agreement, the risk of shortages in deliveries under the contract may increase after 2060 depending upon future storage, hydrologic conditions, and other factors. Section 11(a) of Public Law 87-483 allows for contracting of water from Navajo Reservoir up to a total amount that, in the event of shortage, still results in a reasonable amount of water being available for the diversion requirements of the NIIP and the San Juan-Chama Project.

VIII. Disclaimers

A. Interstate Compacts and Federal Laws

Nothing in this report is intended to interpret the provisions of the Colorado River Compact (45 Stat. 1057), the Upper Colorado River Basin Compact (63 Stat. 31), the Water Treaty of 1944 between the United States of America and the United Mexican States (59 Stat. 1219), the decree entered by the Supreme Court of the United States in *Arizona v. California*, *et al.* (376 U.S. 340), the Boulder Canyon Project Act (45 Stat.

1057), the Boulder Canyon Project Adjustment Act (54 Stat. 774), the Colorado River Storage Project Act (70 Stat. 105), or the Colorado River Basin Project Act (82 Stat. 885). Implementation of the Navajo-Gallup Water Supply Project and the NIIP is subject to compliance with federal environmental laws including the National Environmental Policy Act and the Endangered Species Act.

B. Proposed Navajo Reservoir Water Contract

This determination is not to be construed as acceptance by the Department of the Interior of the terms of the Settlement Agreement, including the terms of the proposed contract. This determination also does not guarantee that the United States would be able to deliver water under the proposed contract without shortages in deliveries on account of drought or other causes outside the control of the Secretary. Nothing in this determination shall be construed to impose on the United States any obligation to maintain CRSP storage facilities, including Navajo Dam and Reservoir, or NIIP or Navajo-Gallup Water Supply Project facilities beyond their useful lives or to take extraordinary measures to keep these facilities operating.

List of Appendices

APPENDIX A - Mass Balance Analysis

Upper Basin Yield Mass Balance Analysis

Run 1 - Maintain CRSP Minimum Power Pools, 8.25 maf Lower Basin Delivery, No Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	29,530,030	24,847,704	8,250,000	5,550,000	749,290	33,530,761	4,000,731	0	29,530,030	24,847,704
1907	21,201,694	29,530,030	24,847,704	8,250,000	5,550,000	749,290	36,182,434	6,652,404	0	29,530,030	24,847,704
1908	12,218,817	29,530,030	24,847,704	8,250,000	5,550,000	725,218	27,223,629	0	0	27,223,629	22,907,009
1909	22,356,301	27,223,629	22,907,009	8,250,000	5,550,000	725,218	35,054,712	5,524,682	0	29,530,030	24,847,704
1910	14,650,616	29,530,030	24,847,704	8,250,000	5,550,000	749,290	29,631,356	101,326	0	29,530,030	24,847,704
1911	15,499,729	29,530,030	24,847,704	8,250,000	5,550,000	749,290	30,480,469	950,439	0	29,530,030	24,847,704
1912	18,623,410	29,530,030	24,847,704	8,250,000	5,550,000	749,290	33,604,150	4,074,120	0	29,530,030	24,847,704
1913	14,536,373	29,530,030	24,847,704	8,250,000	5,550,000	749,157	29,517,247	0	0	29,517,247	24,836,947
1914	21,354,814	29,517,247	24,836,947	8,250,000	5,550,000	749,157	36,322,904	6,792,873	0	29,530,030	24,847,704
1915	13,623,277	29,530,030	24,847,704	8,250,000	5,550,000	739,725	28,613,582	0	0	28,613,582	24,076,569
1916	20,142,892	28,613,582	24,076,569	8,250,000	5,550,000	739,725	34,216,749	4,686,719	0	29,530,030	24,847,704
1917	22,942,804	29,530,030	24,847,704	8,250,000	5,550,000	749,290	37,923,544	8,393,514	0	29,530,030	24,847,704
1918	15,865,939	29,530,030	24,847,704	8,250,000	5,550,000	749,290	30,846,679	1,316,649	0	29,530,030	24,847,704
1919	12,651,369	29,530,030	24,847,704	8,250,000	5,550,000	729,686	27,651,713	0	0	27,651,713	23,267,216
1920	22,287,632	27,651,713	23,267,216	8,250,000	5,550,000	729,686	35,409,659	5,879,629	0	29,530,030	24,847,704
1921	22,526,781	29,530,030	24,847,704	8,250,000	5,550,000	749,290	37,507,521	7,977,491	0	29,530,030	24,847,704
1922	18,447,198	29,530,030	24,847,704	8,250,000	5,550,000	749,290	33,427,938	3,897,908	0	29,530,030	24,847,704
1923	19,024,046	29,530,030	24,847,704	8,250,000	5,550,000	749,290	34,004,786	4,474,756	0	29,530,030	24,847,704
1924	13,877,798	29,530,030	24,847,704	8,250,000	5,550,000	742,354	28,865,474	0	0	28,865,474	24,288,521
1925	14,430,701	28,865,474	24,288,521	8,250,000	5,550,000	734,337	28,761,839	0	0	28,761,839	24,201,318
1926	15,213,731	28,761,839	24,201,318	8,250,000	5,550,000	740,284	29,435,286	0	0	29,435,286	24,767,982
1927	19,539,212	29,435,286	24,767,982	8,250,000	5,550,000	748,301	34,426,197	4,896,166	0	29,530,030	24,847,704
1928	16,954,334	29,530,030	24,847,704	8,250,000	5,550,000	749,290	31,935,074	2,405,044	0	29,530,030	24,847,704
1929	21,829,585	29,530,030	24,847,704	8,250,000	5,550,000	749,290	36,810,325	7,280,295	0	29,530,030	24,847,704
1930	14,621,041	29,530,030	24,847,704	8,250,000	5,550,000	749,290	29,601,781	71,751	0	29,530,030	24,847,704
1931	8,474,134	29,530,030	24,847,704	8,250,000	5,550,000	686,538	23,517,626	0	0	23,517,626	19,788,636
1932	17,422,187	23,517,626	19,788,636	8,250,000	5,550,000	654,758	26,485,055	0	0	26,485,055	22,285,545
1933	12,183,500	26,485,055	22,285,545	8,250,000	5,550,000	661,949	24,206,607	0	0	24,206,607	20,368,371
1934	6,178,192	24,206,607	20,368,371	8,250,000	5,550,000	552,849	16,031,950	0	0	16,031,950	13,489,900
1935	12,630,349	16,031,950	13,489,900	8,250,000	5,550,000	450,618	14,411,681	0	0	14,411,681	12,126,543
1936	14,648,873	14,411,681	12,126,543	8,250,000	5,550,000	437,996	14,822,558	0	0	14,822,558	12,472,271
1937	14,306,056	14,822,558	12,472,271	8,250,000	5,550,000	442,943	14,885,671	0	0	14,885,671	12,525,376
1938	18,148,319	14,885,671	12,525,376	8,250,000	5,550,000	483,935	18,750,055	0	0	18,750,055	15,777,018
1939	11,164,059	18,750,055	15,777,018	8,250,000	5,550,000	491,625	15,622,489	0	0	15,622,489	13,145,364
1940	9,931,657	15,622,489	13,145,364	8,250,000	5,550,000	414,284	11,339,862	0	0	11,339,862	9,541,797
1941	20,116,678	11,339,862	9,541,797	8,250,000	5,550,000	431,015	17,225,525	0	0	17,225,525	14,494,220
1942	17,225,136	17,225,525	14,494,220	8,250,000	5,550,000	522,737	20,127,925	0	0	20,127,925	16,936,410
1943	13,731,401	20,127,925	16,936,410	8,250,000	5,550,000	546,608	19,512,717	0	0	19,512,717	16,418,751
1944	15,369,422	19,512,717	16,418,751	8,250,000	5,550,000	550,819	20,531,321	0	0	20,531,321	17,275,843
1945	14,140,528	20,531,321	17,275,843	8,250,000	5,550,000	559,168	20,312,681	0	0	20,312,681	17,091,871
1946	11,095,453	20,312,681	17,091,871	8,250,000	5,550,000	523,198	17,084,936	0	0	17,084,936	14,375,923
1947	16,439,486	17,084,936	14,375,923	8,250,000	5,550,000	511,717	19,212,705	0	0	19,212,705	16,166,309
1948	15,139,294	19,212,705	16,166,309	8,250,000	5,550,000	542,244	20,009,755	0	0	20,009,755	16,836,978
1949	16,933,584	20,009,755	16,836,978	8,250,000	5,550,000	577,243	22,566,096	0	0	22,566,096	18,987,982
1950	13,140,416	22,566,096	18,987,982	8,250,000	5,550,000	590,873	21,315,639	0	0	21,315,639	17,935,799
1951	12,505,894	21,315,639	17,935,799	8,250,000	5,550,000	558,486	19,463,047	0	0	19,463,047	16,376,957
1952	20,805,422	19,463,047	16,376,957	8,250,000	5,550,000	605,942	25,862,527	0	0	25,862,527	21,761,725
1953	11,165,419	25,862,527	21,761,725	8,250,000	5,550,000	638,572	22,589,374	0	0	22,589,374	19,007,568
1954	8,496,102	22,589,374	19,007,568	8,250,000	5,550,000	543,381	16,742,094	0	0	16,742,094	14,087,442
1955	9,413,908	16,742,094	14,087,442	8,250,000	5,550,000	432,065	11,923,937	0	0	11,923,937	10,033,259
1956	11,426,874	11,923,937	10,033,259	8,250,000	5,550,000	353,322	9,197,489	0	0	9,197,489	7,739,121
1957	21,500,963	9,197,489	7,739,121	8,250,000	5,550,000	401,055	16,497,397	0	0	16,497,397	13,881,544
1958	15,862,511	16,497,397	13,881,544	8,250,000	5,550,000	493,620	18,066,288	0	0	18,066,288	15,201,670
1959	9,598,169	18,066,288	15,201,670	8,250,000	5,550,000	461,325	13,403,132	0	0	13,403,132	11,277,911
1960	11,524,160	13,403,132	11,277,911	8,250,000	5,550,000	384,885	10,742,407	0	0	10,742,407	9,039,075
1961	10,010,259	10,742,407	9,039,075	8,250,000	5,550,000	314,281	6,638,386	0	0	6,638,386	5,585,793
1962	17,377,609	6,638,386	5,585,793	8,250,000	5,550,000	305,597	9,910,398	0	0	9,910,398	8,338,990
1963	8,840,900	9,910,398	8,338,990	8,250,000	5,550,000	285,014	4,666,284	0	0	4,666,284	3,926,391
1964	10,863,586	4,666,284	3,926,391	8,250,000	5,550,000	197,571	1,532,299	0	0	1,532,299	1,289,335
1965	19,875,027	1,532,299	1,289,335	8,250,000	5,550,000	225,909	7,381,417	0	0	7,381,417	6,211,008
1966	10,679,844	7,381,417	6,211,008	8,250,000	5,550,000	251,764	4,009,497	0	0	4,009,497	3,373,745
1967	11,670,830	4,009,497	3,373,745	8,250,000	5,550,000	192,341	1,687,986	0	0	1,687,986	1,420,336
1968	13,739,932	1,687,986	1,420,336	8,250,000	5,550,000	165,754	1,462,164	0	0	1,462,164	1,230,321
1969	15,272,159	1,462,164	1,230,321	8,250,000	5,550,000	176,916	2,757,407	0	0	2,757,407	2,320,188
1970	15,344,136	2,757,407	2,320,188	8,250,000	5,550,000	204,417	4,097,125	0	0	4,097,125	3,447,479
1971	15,493,659	4,097,125	3,447,479	8,250,000	5,550,000	233,638	5,557,146	0	0	5,557,146	4,675,996
1972	13,186,637	5,557,146	4,675,996	8,250,000	5,550,000	239,970	4,703,812	0	0	4,703,812	3,957,968
1973	18,650,193	4,703,812	3,957,968	8,250,000	5,550,000	278,776	9,275,229	0	0	9,275,229	7,804,534
1974	13,285,426	9,275,229	7,804,534	8,250,000	5,550,000	317,801	8,442,854	0	0	8,442,854	7,104,142
1975	17,072,661	8,442,854	7,104,142	8,250,000	5,550,000	339,725	11,375,790	0	0	11,375,790	9,572,028
1976	11,313,561	11,375,790	9,572,028	8,250,000	5,550,000	340,828	8,548,524	0	0	8,548,524	7,193,057
1977	5,551,188	8,548,524	7,193,057	8,250,000	5,550,000	222,899	76,813	0	0	76,813	64,633
1978	15,335,909	76,813	64,633	8,250,000	5,550,000	148,955	1,463,766	0	0	1,463,766	1,231,669
1979	17,825,429	1,463,766	1,231,669	8,250,000	5,550,000	203,322	5,285,872	0	0	5,285,872	4,447,736
1980	17,927,076	5,285,872	4,447,736	8,250,000	5,550,000	283,332	9,129,617	0	0	9,129,617	7,682,011
1981	9,015,200	9,129,617	7,682,011	8,250,000	5,550,000	270,684	4,074,132	0	0	4,074,132	3,428,132
1982	17,489,400	4,074,132	3,428,132	8,250,000	5,550,000	253,778	7,509,754	0	0	7,509,754	6,318,996
1983	24,361,989	7,509,754	6,318,996	8,250,000	5,550,000	395,742	17,676,001	0	0	17,676,001	14,873,268
1984	25,359,376	17,676,001	14,873,268	8,250,000	5,550,000	616,064	28,619,314	0	0	28,619,314	24,081,392
1985	21,246,109	28,619,314	24,081,392	8,250,000	5,550,000	739,785	35,325,638	5,795,607	0	29,530,030	24,847,704
1986	23,013,446	29,530,030	24,847,704	8,250,000	5,550,000	749,290	37,994,186	8,464,156	0	29,530,030	24,847,704
1987	15,640,478	29,530,030	24,847,704	8,250,000	5,550,000	749,290	30,621,219	1,091,188	0	29,530,030	24,847,704
1988	11,456,357	29,530,030	24,847,704	8,250,000	5,550,000	717,342	26,469,044	0	0	26,469,044	22,272,073
1989	9,921,847	26,469,044	22,272,073	8,250,000	5,550,000	638,257	21,952,634	0	0	21,952,634	18,471,791
1990	9,639,803	21,952,634	18,471,791	8,250,000	5,550,000	542,041	17,250,397	0	0	17,250,397	14,515,148
1991	12,170,021	17,250,397	14,515,148	8,250,000	5,550,000	471,035	15,149,382	0	0	15,149,382	12,747,273
1992	10,895,580	15,149,382	12,747,273	8,250,000	5,550,000	414,467	11,830,495	0	0	11,830,495	9,954,634
1993	18,160,118	11,830,495	9,954,634	8,250,000	5,550,000	420,941	15,769,672	0	0	15,769,672	13,269,209
1994	11,125,503	15,769,672	13,269,209	8,250,000	5,550,000	429,656	12,665,519	0	0	12,665,519	10,657,255
1995	20,047,166	12,665,519	10,657,255	8,250,000	5,550,000	457,683	18,455,001	0	0	18,455,001	15,528,748
1996	14,502,293	18,455,001	15,528,748	8,250,000	5,550,000	520,011	18,637,284	0	0	18,637,284	15,682,128
1997	21,622,438	18,637,284	15,682,128	8,250,000	5,550,000	597,322	25,862,399	0	0	25,862,399	21,761,618
1998	16,798,378	25,862,399	21,761,618	8,250,000	5,550,000	696,754	28,164,023	0	0	28,164,023	23,698,293
1999	15,934,210	28,164,023	23,698,293	8,250,000	5,550,000	735,033	29,563,200	33,170	0	29,530,030	24,847,704
2000	10,646,526	29,530,030	24,847,704	8,250,000	5,550,000	708,978	25,667,579	0	0	25,667,579	21,597,689
Total									0		
Averages:											
1953-1977	13,088,628			8,250,000	5,550,000	320,057		0	0	8,451,410	7,111,342
1931-1977	13,594,590			8,250,000	5,550,000	421,255		0	0	13,501,780	11,360,918
1906-2000	15,284,742			8,250,000	5,550,000	527,920		997,480	0	18,904,684	15,907,129

Variables

Storage	30,167,576 af
Sedimentation Rate (Active)	24,292 af/yr
Bank Storage	4%
Adjusted Storage (2060)	29,530,030 af
UB Demand Level	5,550,000 af/yr
LB Delivery	8,250,000 af/yr

Results

Average CRSP Evap	527,920 af/yr
Total Yield w/ CRSP evap	6,077,920 af/yr

Shortage Years	**Shortage**
1963	0 af
1964	0 af
1967	0 af
1968	0 af
1977	0 af

NM allocation(w/o evap) 618,750 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	5,870,057 af/yr
1931-1977	5,971,255 af/yr
1906-2000	6,077,920 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	0.00%
1931-1977	0.00%
1906-2000	0.00%

Upper Basin Yield Mass Balance Analysis

Run 2 - Maintain CRSP Minimum Power Pools, 8.25 maf Lower Basin Delivery, 6% Overall Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	29,530,030	24,847,704	8,250,000	5,790,000	749,290	33,290,761	3,760,731	0	29,530,030	24,847,704
1907	21,201,694	29,530,030	24,847,704	8,250,000	5,790,000	749,290	35,942,434	6,412,404	0	29,530,030	24,847,704
1908	12,218,817	29,530,030	24,847,704	8,250,000	5,790,000	722,739	26,986,108	0	0	26,986,108	22,707,150
1909	22,356,301	26,986,108	22,707,150	8,250,000	5,790,000	722,739	34,579,670	5,049,640	0	29,530,030	24,847,704
1910	14,650,616	29,530,030	24,847,704	8,250,000	5,790,000	747,858	29,392,789	0	0	29,392,789	24,732,223
1911	15,499,729	29,392,789	24,732,223	8,250,000	5,790,000	747,858	30,104,660	574,629	0	29,530,030	24,847,704
1912	18,623,410	29,530,030	24,847,704	8,250,000	5,790,000	749,290	33,364,150	3,834,120	0	29,530,030	24,847,704
1913	14,536,373	29,530,030	24,847,704	8,250,000	5,790,000	746,678	29,279,726	0	0	29,279,726	24,637,088
1914	21,354,814	29,279,726	24,637,088	8,250,000	5,790,000	746,678	35,847,862	6,317,832	0	29,530,030	24,847,704
1915	13,623,277	29,530,030	24,847,704	8,250,000	5,790,000	737,246	28,376,061	0	0	28,376,061	23,876,710
1916	20,142,892	28,376,061	23,876,710	8,250,000	5,790,000	737,246	33,741,707	4,211,677	0	29,530,030	24,847,704
1917	22,942,804	29,530,030	24,847,704	8,250,000	5,790,000	749,290	37,683,544	8,153,514	0	29,530,030	24,847,704
1918	15,865,939	29,530,030	24,847,704	8,250,000	5,790,000	749,290	30,606,679	1,076,649	0	29,530,030	24,847,704
1919	12,651,369	29,530,030	24,847,704	8,250,000	5,790,000	727,207	27,414,192	0	0	27,414,192	23,067,356
1920	22,287,632	27,414,192	23,067,356	8,250,000	5,790,000	727,207	34,934,617	5,404,587	0	29,530,030	24,847,704
1921	22,526,781	29,530,030	24,847,704	8,250,000	5,790,000	749,290	37,267,521	7,737,491	0	29,530,030	24,847,704
1922	18,447,198	29,530,030	24,847,704	8,250,000	5,790,000	749,290	33,187,938	3,657,908	0	29,530,030	24,847,704
1923	19,024,046	29,530,030	24,847,704	8,250,000	5,790,000	749,290	33,764,786	4,234,756	0	29,530,030	24,847,704
1924	13,877,798	29,530,030	24,847,704	8,250,000	5,790,000	739,875	28,627,953	0	0	28,627,953	24,088,662
1925	14,430,701	28,627,953	24,088,662	8,250,000	5,790,000	726,951	28,291,704	0	0	28,291,704	23,805,728
1926	15,213,731	28,291,704	23,805,728	8,250,000	5,790,000	728,092	28,737,342	0	0	28,737,342	24,180,706
1927	19,539,212	28,737,342	24,180,706	8,250,000	5,790,000	741,017	33,495,537	3,965,507	0	29,530,030	24,847,704
1928	16,954,334	29,530,030	24,847,704	8,250,000	5,790,000	749,290	31,695,074	2,165,044	0	29,530,030	24,847,704
1929	21,829,585	29,530,030	24,847,704	8,250,000	5,790,000	749,290	36,570,325	7,040,295	0	29,530,030	24,847,704
1930	14,621,041	29,530,030	24,847,704	8,250,000	5,790,000	747,552	29,363,519	0	0	29,363,519	24,707,595
1931	8,474,134	29,363,519	24,707,595	8,250,000	5,790,000	680,619	23,117,034	0	0	23,117,034	19,451,562
1932	17,422,187	23,117,034	19,451,562	8,250,000	5,790,000	644,003	25,855,218	0	0	25,855,218	21,755,575
1933	12,183,500	25,855,218	21,755,575	8,250,000	5,790,000	646,458	23,352,260	0	0	23,352,260	19,649,490
1934	6,178,192	23,352,260	19,649,490	8,250,000	5,790,000	532,720	14,957,731	0	0	14,957,731	12,586,011
1935	12,630,349	14,957,731	12,586,011	8,250,000	5,790,000	425,948	13,122,133	0	0	13,122,133	11,041,468
1936	14,648,873	13,122,133	11,041,468	8,250,000	5,790,000	408,877	13,322,129	0	0	13,322,129	11,209,752
1937	14,306,056	13,322,129	11,209,752	8,250,000	5,790,000	409,467	13,178,718	0	0	13,178,718	11,089,080
1938	18,148,319	13,178,718	11,089,080	8,250,000	5,790,000	446,192	16,840,844	0	0	16,840,844	14,170,535
1939	11,164,059	16,840,844	14,170,535	8,250,000	5,790,000	449,704	13,515,199	0	0	13,515,199	11,372,209
1940	9,931,657	13,515,199	11,372,209	8,250,000	5,790,000	368,272	9,038,585	0	0	9,038,585	7,605,413
1941	20,116,678	9,038,585	7,605,413	8,250,000	5,790,000	380,995	14,734,268	0	0	14,734,268	12,397,980
1942	17,225,136	14,734,268	12,397,980	8,250,000	5,790,000	468,792	17,450,612	0	0	17,450,612	14,683,616
1943	13,731,401	17,450,612	14,683,616	8,250,000	5,790,000	488,820	16,653,193	0	0	16,653,193	14,012,637
1944	15,369,422	16,653,193	14,012,637	8,250,000	5,790,000	489,266	17,493,349	0	0	17,493,349	14,719,577
1945	14,140,528	17,493,349	14,719,577	8,250,000	5,790,000	493,929	17,099,948	0	0	17,099,948	14,388,554
1946	11,095,453	17,099,948	14,388,554	8,250,000	5,790,000	454,348	13,701,053	0	0	13,701,053	11,528,593
1947	16,439,486	13,701,053	11,528,593	8,250,000	5,790,000	439,332	15,661,207	0	0	15,661,207	13,177,942
1948	15,139,294	15,661,207	13,177,942	8,250,000	5,790,000	466,396	16,294,105	0	0	16,294,105	13,710,487
1949	16,933,584	16,294,105	13,710,487	8,250,000	5,790,000	498,004	18,689,684	0	0	18,689,684	15,726,220
1950	13,140,416	18,689,684	15,726,220	8,250,000	5,790,000	508,313	17,281,788	0	0	17,281,788	14,541,561
1951	12,505,894	17,281,788	14,541,561	8,250,000	5,790,000	472,674	15,275,008	0	0	15,275,008	12,852,979
1952	20,805,422	15,275,008	12,852,979	8,250,000	5,790,000	516,945	21,523,485	0	0	21,523,485	18,110,689
1953	11,165,419	21,523,485	18,110,689	8,250,000	5,790,000	546,455	18,102,449	0	0	18,102,449	15,232,098
1954	8,496,102	18,102,449	15,232,098	8,250,000	5,790,000	448,209	12,110,342	0	0	12,110,342	10,190,108
1955	9,413,908	12,110,342	10,190,108	8,250,000	5,790,000	333,901	7,150,349	0	0	7,150,349	6,016,579
1956	11,426,874	7,150,349	6,016,579	8,250,000	5,790,000	252,228	4,284,996	0	0	4,284,996	3,605,560
1957	21,500,963	4,284,996	3,605,560	8,250,000	5,790,000	297,091	11,448,867	0	0	11,448,867	9,633,517
1958	15,862,511	11,448,867	9,633,517	8,250,000	5,790,000	386,845	12,884,533	0	0	12,884,533	10,841,542
1959	9,598,169	12,884,533	10,841,542	8,250,000	5,790,000	351,798	8,090,903	0	0	8,090,903	6,807,998
1960	11,524,160	8,090,903	6,807,998	8,250,000	5,790,000	272,663	5,302,401	0	0	5,302,401	4,461,644
1961	10,010,259	5,302,401	4,461,644	8,250,000	5,790,000	199,419	1,073,241	0	0	1,073,241	903,066
1962	17,377,609	1,073,241	903,066	8,250,000	5,790,000	188,150	4,222,699	0	0	4,222,699	3,553,142
1963	8,840,900	4,222,699	3,553,142	8,250,000	5,790,000	176,949	-1,153,349	0	1,153,349	0	0
1964	10,863,586	0	0	8,250,000	5,790,000	132,876	-3,309,290	0	3,309,290	0	0
1965	19,875,027	0	0	8,250,000	5,790,000	191,775	5,643,252	0	0	5,643,252	4,748,449
1966	10,679,844	5,643,252	4,748,449	8,250,000	5,790,000	213,377	2,069,719	0	0	2,069,719	1,741,541
1967	11,670,830	2,069,719	1,741,541	8,250,000	5,790,000	154,478	-453,929	0	453,929	0	0
1968	13,739,932	0	0	8,250,000	5,790,000	132,876	-432,944	0	432,944	0	0
1969	15,272,159	0	0	8,250,000	5,790,000	144,231	1,087,928	0	0	1,087,928	915,425
1970	15,344,136	1,087,928	915,425	8,250,000	5,790,000	167,449	2,224,615	0	0	2,224,615	1,871,877
1971	15,493,659	2,224,615	1,871,877	8,250,000	5,790,000	192,476	3,485,798	0	0	3,485,798	2,933,084
1972	13,186,637	3,485,798	2,933,084	8,250,000	5,790,000	194,700	2,437,734	0	0	2,437,734	2,051,203
1973	18,650,193	2,437,734	2,051,203	8,250,000	5,790,000	229,483	6,818,443	0	0	6,818,443	5,737,301
1974	13,285,426	6,818,443	5,737,301	8,250,000	5,790,000	264,568	5,799,301	0	0	5,799,301	4,879,755
1975	17,072,661	5,799,301	4,879,755	8,250,000	5,790,000	282,634	8,549,329	0	0	8,549,329	7,193,734
1976	11,313,561	8,549,329	7,193,734	8,250,000	5,790,000	279,958	5,542,932	0	0	5,542,932	4,664,036
1977	5,551,188	5,542,932	4,664,036	8,250,000	5,790,000	190,728	-3,136,608	0	3,136,608	0	0
1978	15,335,909	0	0	8,250,000	5,790,000	144,889	1,151,019	0	0	1,151,019	968,512
1979	17,825,429	1,151,019	968,512	8,250,000	5,790,000	194,383	4,742,065	0	0	4,742,065	3,990,156
1980	17,927,076	4,742,065	3,990,156	8,250,000	5,790,000	269,618	8,359,523	0	0	8,359,523	7,034,025
1981	9,015,200	8,359,523	7,034,025	8,250,000	5,790,000	252,296	3,082,427	0	0	3,082,427	2,593,672
1982	17,489,400	3,082,427	2,593,672	8,250,000	5,790,000	230,812	6,301,015	0	0	6,301,015	5,301,916
1983	24,361,989	6,301,015	5,301,916	8,250,000	5,790,000	368,292	16,254,712	0	0	16,254,712	13,677,340
1984	25,359,376	16,254,712	13,677,340	8,250,000	5,790,000	584,223	26,989,865	0	0	26,989,865	22,710,311
1985	21,246,109	26,989,865	22,710,311	8,250,000	5,790,000	722,778	33,473,196	3,943,165	0	29,530,030	24,847,704
1986	23,013,446	29,530,030	24,847,704	8,250,000	5,790,000	749,290	37,754,186	8,224,156	0	29,530,030	24,847,704
1987	15,640,478	29,530,030	24,847,704	8,250,000	5,790,000	749,290	30,381,219	851,188	0	29,530,030	24,847,704
1988	11,456,357	29,530,030	24,847,704	8,250,000	5,790,000	714,863	26,231,523	0	0	26,231,523	22,072,213
1989	9,921,847	26,231,523	22,072,213	8,250,000	5,790,000	630,871	21,482,499	0	0	21,482,499	18,076,202
1990	9,639,803	21,482,499	18,076,202	8,250,000	5,790,000	529,850	16,552,453	0	0	16,552,453	13,927,871
1991	12,170,021	16,552,453	13,927,871	8,250,000	5,790,000	454,137	14,228,336	0	0	14,228,336	11,972,270
1992	10,895,580	14,228,336	11,972,270	8,250,000	5,790,000	392,960	10,690,956	0	0	10,690,956	8,995,781
1993	18,160,118	10,690,956	8,995,781	8,250,000	5,790,000	394,921	14,416,153	0	0	14,416,153	12,130,306
1994	11,125,503	14,416,153	12,130,306	8,250,000	5,790,000	399,215	11,102,440	0	0	11,102,440	9,342,020
1995	20,047,166	11,102,440	9,342,020	8,250,000	5,790,000	422,913	16,686,693	0	0	16,686,693	14,040,825
1996	14,502,293	16,686,693	14,040,825	8,250,000	5,790,000	481,001	16,667,984	0	0	16,667,984	14,025,084
1997	21,622,438	16,667,984	14,025,084	8,250,000	5,790,000	554,161	23,696,262	0	0	23,696,262	19,938,947
1998	16,798,378	23,696,262	19,938,947	8,250,000	5,790,000	649,526	25,805,114	0	0	25,805,114	21,713,416
1999	15,934,210	25,805,114	21,713,416	8,250,000	5,790,000	684,165	27,015,159	0	0	27,015,159	22,731,595
2000	10,646,526	27,015,159	22,731,595	8,250,000	5,790,000	654,545	22,967,140	0	0	22,967,140	19,325,436
Total									8,486,120		
Averages:											
1953-1977	13,088,628			8,250,000	5,790,000	249,013		0	339,445	5,133,193	4,319,266
1931-1977	13,594,590			8,250,000	5,790,000	359,902		0	180,556	10,563,561	8,888,587
1906-2000	15,284,742			8,250,000	5,790,000	491,413		911,740	89,328	17,141,586	14,423,590

Variables

Storage	30,167,576 af
Sedimentation Rate (Active)	24,292 af/yr
Bank Storage	4%
Adjusted Storage (2060)	29,530,030 af
UB Demand Level	5,790,000 af/yr
LB Delivery	8,250,000 af/yr

Results

Average CRSP Evap	491,413 af/yr
Total Yield w/ CRSP evap	6,281,413 af/yr

Shortage Years	**Shortage**
1963	1,153,349 af
1964	3,309,290 af
1967	453,929 af
1968	432,944 af
1977	3,136,608 af

NM allocation(w/o evap) 645,750 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,039,013 af/yr
1931-1977	6,149,902 af/yr
1906-2000	6,281,413 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	5.86%
1931-1977	3.12%
1906-2000	1.54%

Upper Basin Yield Mass Balance Analysis

Run 3 - Maintain CRSP Minimum Power Pools, 7.50 maf Lower Basin Delivery, No Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	29,530,030	24,847,704	7,500,000	6,300,000	749,290	33,530,761	4,000,731	0	29,530,030	24,847,704
1907	21,201,694	29,530,030	24,847,704	7,500,000	6,300,000	749,290	36,182,434	6,652,404	0	29,530,030	24,847,704
1908	12,218,817	29,530,030	24,847,704	7,500,000	6,300,000	725,218	27,223,629	0	0	27,223,629	22,907,009
1909	22,356,301	27,223,629	22,907,009	7,500,000	6,300,000	725,218	35,054,712	5,524,682	0	29,530,030	24,847,704
1910	14,650,616	29,530,030	24,847,704	7,500,000	6,300,000	749,290	29,631,356	101,326	0	29,530,030	24,847,704
1911	15,499,729	29,530,030	24,847,704	7,500,000	6,300,000	749,290	30,480,469	950,439	0	29,530,030	24,847,704
1912	18,623,410	29,530,030	24,847,704	7,500,000	6,300,000	749,290	33,604,150	4,074,120	0	29,530,030	24,847,704
1913	14,536,373	29,530,030	24,847,704	7,500,000	6,300,000	749,157	29,517,247	0	0	29,517,247	24,836,947
1914	21,354,814	29,517,247	24,836,947	7,500,000	6,300,000	749,157	36,322,904	6,792,873	0	29,530,030	24,847,704
1915	13,623,277	29,530,030	24,847,704	7,500,000	6,300,000	739,725	28,613,582	0	0	28,613,582	24,076,569
1916	20,142,892	28,613,582	24,076,569	7,500,000	6,300,000	739,725	34,216,749	4,686,719	0	29,530,030	24,847,704
1917	22,942,804	29,530,030	24,847,704	7,500,000	6,300,000	749,290	37,923,544	8,393,514	0	29,530,030	24,847,704
1918	15,865,939	29,530,030	24,847,704	7,500,000	6,300,000	749,290	30,846,679	1,316,649	0	29,530,030	24,847,704
1919	12,651,369	29,530,030	24,847,704	7,500,000	6,300,000	729,686	27,651,713	0	0	27,651,713	23,267,216
1920	22,287,632	27,651,713	23,267,216	7,500,000	6,300,000	729,686	35,409,659	5,879,629	0	29,530,030	24,847,704
1921	22,526,781	29,530,030	24,847,704	7,500,000	6,300,000	749,290	37,507,521	7,977,491	0	29,530,030	24,847,704
1922	18,447,198	29,530,030	24,847,704	7,500,000	6,300,000	749,290	33,427,938	3,897,908	0	29,530,030	24,847,704
1923	19,024,046	29,530,030	24,847,704	7,500,000	6,300,000	749,290	34,004,786	4,474,756	0	29,530,030	24,847,704
1924	13,877,798	29,530,030	24,847,704	7,500,000	6,300,000	742,354	28,865,474	0	0	28,865,474	24,288,521
1925	14,430,701	28,865,474	24,288,521	7,500,000	6,300,000	734,337	28,761,839	0	0	28,761,839	24,201,318
1926	15,213,731	28,761,839	24,201,318	7,500,000	6,300,000	740,284	29,435,286	0	0	29,435,286	24,767,982
1927	19,539,212	29,435,286	24,767,982	7,500,000	6,300,000	748,301	34,426,197	4,896,166	0	29,530,030	24,847,704
1928	16,954,334	29,530,030	24,847,704	7,500,000	6,300,000	749,290	31,935,074	2,405,044	0	29,530,030	24,847,704
1929	21,829,585	29,530,030	24,847,704	7,500,000	6,300,000	749,290	36,810,325	7,280,295	0	29,530,030	24,847,704
1930	14,621,041	29,530,030	24,847,704	7,500,000	6,300,000	749,290	29,601,781	71,751	0	29,530,030	24,847,704
1931	8,474,134	29,530,030	24,847,704	7,500,000	6,300,000	686,538	23,517,626	0	0	23,517,626	19,788,636
1932	17,422,187	23,517,626	19,788,636	7,500,000	6,300,000	654,758	26,485,055	0	0	26,485,055	22,285,545
1933	12,183,500	26,485,055	22,285,545	7,500,000	6,300,000	661,949	24,206,607	0	0	24,206,607	20,368,371
1934	6,178,192	24,206,607	20,368,371	7,500,000	6,300,000	552,849	16,031,950	0	0	16,031,950	13,489,900
1935	12,630,349	16,031,950	13,489,900	7,500,000	6,300,000	450,618	14,411,681	0	0	14,411,681	12,126,543
1936	14,648,873	14,411,681	12,126,543	7,500,000	6,300,000	437,996	14,822,558	0	0	14,822,558	12,472,271
1937	14,306,056	14,822,558	12,472,271	7,500,000	6,300,000	442,943	14,885,671	0	0	14,885,671	12,525,376
1938	18,148,319	14,885,671	12,525,376	7,500,000	6,300,000	483,935	18,750,055	0	0	18,750,055	15,777,018
1939	11,164,059	18,750,055	15,777,018	7,500,000	6,300,000	491,625	15,622,489	0	0	15,622,489	13,145,364
1940	9,931,657	15,622,489	13,145,364	7,500,000	6,300,000	414,284	11,339,862	0	0	11,339,862	9,541,797
1941	20,116,678	11,339,862	9,541,797	7,500,000	6,300,000	431,015	17,225,525	0	0	17,225,525	14,494,220
1942	17,225,136	17,225,525	14,494,220	7,500,000	6,300,000	522,737	20,127,925	0	0	20,127,925	16,936,410
1943	13,731,401	20,127,925	16,936,410	7,500,000	6,300,000	546,608	19,512,717	0	0	19,512,717	16,418,751
1944	15,369,422	19,512,717	16,418,751	7,500,000	6,300,000	550,819	20,531,321	0	0	20,531,321	17,275,843
1945	14,140,528	20,531,321	17,275,843	7,500,000	6,300,000	559,168	20,312,681	0	0	20,312,681	17,091,871
1946	11,095,453	20,312,681	17,091,871	7,500,000	6,300,000	523,198	17,084,936	0	0	17,084,936	14,375,923
1947	16,439,486	17,084,936	14,375,923	7,500,000	6,300,000	511,717	19,212,705	0	0	19,212,705	16,166,309
1948	15,139,294	19,212,705	16,166,309	7,500,000	6,300,000	542,244	20,009,755	0	0	20,009,755	16,836,978
1949	16,933,584	20,009,755	16,836,978	7,500,000	6,300,000	577,243	22,566,096	0	0	22,566,096	18,987,982
1950	13,140,416	22,566,096	18,987,982	7,500,000	6,300,000	590,873	21,315,639	0	0	21,315,639	17,935,799
1951	12,505,894	21,315,639	17,935,799	7,500,000	6,300,000	558,486	19,463,047	0	0	19,463,047	16,376,957
1952	20,805,422	19,463,047	16,376,957	7,500,000	6,300,000	605,942	25,862,527	0	0	25,862,527	21,761,725
1953	11,165,419	25,862,527	21,761,725	7,500,000	6,300,000	638,572	22,589,374	0	0	22,589,374	19,007,568
1954	8,496,102	22,589,374	19,007,568	7,500,000	6,300,000	543,381	16,742,094	0	0	16,742,094	14,087,442
1955	9,413,908	16,742,094	14,087,442	7,500,000	6,300,000	432,065	11,923,937	0	0	11,923,937	10,033,259
1956	11,426,874	11,923,937	10,033,259	7,500,000	6,300,000	353,322	9,197,489	0	0	9,197,489	7,739,121
1957	21,500,963	9,197,489	7,739,121	7,500,000	6,300,000	401,055	16,497,397	0	0	16,497,397	13,881,544
1958	15,862,511	16,497,397	13,881,544	7,500,000	6,300,000	493,620	18,066,288	0	0	18,066,288	15,201,670
1959	9,598,169	18,066,288	15,201,670	7,500,000	6,300,000	461,325	13,403,132	0	0	13,403,132	11,277,911
1960	11,524,160	13,403,132	11,277,911	7,500,000	6,300,000	384,885	10,742,407	0	0	10,742,407	9,039,075
1961	10,010,259	10,742,407	9,039,075	7,500,000	6,300,000	314,281	6,638,386	0	0	6,638,386	5,585,793
1962	17,377,609	6,638,386	5,585,793	7,500,000	6,300,000	305,597	9,910,398	0	0	9,910,398	8,338,990
1963	8,840,900	9,910,398	8,338,990	7,500,000	6,300,000	285,014	4,666,284	0	0	4,666,284	3,926,391
1964	10,863,586	4,666,284	3,926,391	7,500,000	6,300,000	197,571	1,532,299	0	0	1,532,299	1,289,335
1965	19,875,027	1,532,299	1,289,335	7,500,000	6,300,000	225,909	7,381,417	0	0	7,381,417	6,211,008
1966	10,679,844	7,381,417	6,211,008	7,500,000	6,300,000	251,764	4,009,497	0	0	4,009,497	3,373,745
1967	11,670,830	4,009,497	3,373,745	7,500,000	6,300,000	192,341	1,687,986	0	0	1,687,986	1,420,336
1968	13,739,932	1,687,986	1,420,336	7,500,000	6,300,000	165,754	1,462,164	0	0	1,462,164	1,230,321
1969	15,272,159	1,462,164	1,230,321	7,500,000	6,300,000	176,916	2,757,407	0	0	2,757,407	2,320,188
1970	15,344,136	2,757,407	2,320,188	7,500,000	6,300,000	204,417	4,097,125	0	0	4,097,125	3,447,479
1971	15,493,659	4,097,125	3,447,479	7,500,000	6,300,000	233,638	5,557,146	0	0	5,557,146	4,675,996
1972	13,186,637	5,557,146	4,675,996	7,500,000	6,300,000	239,970	4,703,812	0	0	4,703,812	3,957,968
1973	18,650,193	4,703,812	3,957,968	7,500,000	6,300,000	278,776	9,275,229	0	0	9,275,229	7,804,534
1974	13,285,426	9,275,229	7,804,534	7,500,000	6,300,000	317,801	8,442,854	0	0	8,442,854	7,104,142
1975	17,072,661	8,442,854	7,104,142	7,500,000	6,300,000	339,725	11,375,790	0	0	11,375,790	9,572,028
1976	11,313,561	11,375,790	9,572,028	7,500,000	6,300,000	340,828	8,548,524	0	0	8,548,524	7,193,057
1977	5,551,188	8,548,524	7,193,057	7,500,000	6,300,000	222,899	76,813	0	0	76,813	64,633
1978	15,335,909	76,813	64,633	7,500,000	6,300,000	148,955	1,463,766	0	0	1,463,766	1,231,669
1979	17,825,429	1,463,766	1,231,669	7,500,000	6,300,000	203,322	5,285,872	0	0	5,285,872	4,447,736
1980	17,927,076	5,285,872	4,447,736	7,500,000	6,300,000	283,332	9,129,617	0	0	9,129,617	7,682,011
1981	9,015,200	9,129,617	7,682,011	7,500,000	6,300,000	270,684	4,074,132	0	0	4,074,132	3,428,132
1982	17,489,400	4,074,132	3,428,132	7,500,000	6,300,000	253,778	7,509,754	0	0	7,509,754	6,318,996
1983	24,361,989	7,509,754	6,318,996	7,500,000	6,300,000	395,742	17,676,001	0	0	17,676,001	14,873,268
1984	25,359,376	17,676,001	14,873,268	7,500,000	6,300,000	616,064	28,619,314	0	0	28,619,314	24,081,392
1985	21,246,109	28,619,314	24,081,392	7,500,000	6,300,000	739,785	35,325,638	5,795,607	0	29,530,030	24,847,704
1986	23,013,446	29,530,030	24,847,704	7,500,000	6,300,000	749,290	37,994,186	8,464,156	0	29,530,030	24,847,704
1987	15,640,478	29,530,030	24,847,704	7,500,000	6,300,000	749,290	30,621,219	1,091,188	0	29,530,030	24,847,704
1988	11,456,357	29,530,030	24,847,704	7,500,000	6,300,000	717,342	26,469,044	0	0	26,469,044	22,272,073
1989	9,921,847	26,469,044	22,272,073	7,500,000	6,300,000	638,257	21,952,634	0	0	21,952,634	18,471,791
1990	9,639,803	21,952,634	18,471,791	7,500,000	6,300,000	542,041	17,250,397	0	0	17,250,397	14,515,148
1991	12,170,021	17,250,397	14,515,148	7,500,000	6,300,000	471,035	15,149,382	0	0	15,149,382	12,747,273
1992	10,895,580	15,149,382	12,747,273	7,500,000	6,300,000	414,467	11,830,495	0	0	11,830,495	9,954,634
1993	18,160,118	11,830,495	9,954,634	7,500,000	6,300,000	420,941	15,769,672	0	0	15,769,672	13,269,209
1994	11,125,503	15,769,672	13,269,209	7,500,000	6,300,000	429,656	12,665,519	0	0	12,665,519	10,657,255
1995	20,047,166	12,665,519	10,657,255	7,500,000	6,300,000	457,683	18,455,001	0	0	18,455,001	15,528,748
1996	14,502,293	18,455,001	15,528,748	7,500,000	6,300,000	520,011	18,637,284	0	0	18,637,284	15,682,128
1997	21,622,438	18,637,284	15,682,128	7,500,000	6,300,000	597,322	25,862,399	0	0	25,862,399	21,761,618
1998	16,798,378	25,862,399	21,761,618	7,500,000	6,300,000	696,754	28,164,023	0	0	28,164,023	23,698,293
1999	15,934,210	28,164,023	23,698,293	7,500,000	6,300,000	735,033	29,563,200	33,170	0	29,530,030	24,847,704
2000	10,646,526	29,530,030	24,847,704	7,500,000	6,300,000	708,978	25,667,579	0	0	25,667,579	21,597,689
Total									0		
Averages:											
1953-1977	13,088,628			7,500,000	6,300,000	320,057		0	0	8,451,410	7,111,342
1931-1977	13,594,590			7,500,000	6,300,000	421,255		0	0	13,501,780	11,360,918
1906-2000	15,284,742			7,500,000	6,300,000	527,920		997,480	0	18,904,684	15,907,129

Variables

Storage	30,167,576 af
Sedimentation Rate (Active)	24,292 af/yr
Bank Storage	4%
Adjusted Storage (2060)	29,530,030 af
UB Demand Level	6,300,000 af/yr
LB Delivery	7,500,000 af/yr

Results

Average CRSP Evap	527,920 af/yr
Total Yield w/ CRSP evap	6,827,920 af/yr

Shortage Years	**Shortage**
1963	0 af
1964	0 af
1967	0 af
1968	0 af
1977	0 af

NM allocation(w/o evap) 703,125 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,620,057 af/yr
1931-1977	6,721,255 af/yr
1906-2000	6,827,920 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	0.00%
1931-1977	0.00%
1906-2000	0.00%

Upper Basin Yield Mass Balance Analysis

Run 4 - Maintain CRSP Minimum Power Pools, 7.50 maf Lower Basin Delivery, 6% Overall Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	29,530,030	24,847,704	7,500,000	6,570,000	749,290	33,260,761	3,730,731	0	29,530,030	24,847,704
1907	21,201,694	29,530,030	24,847,704	7,500,000	6,570,000	749,290	35,912,434	6,382,404	0	29,530,030	24,847,704
1908	12,218,817	29,530,030	24,847,704	7,500,000	6,570,000	722,429	26,956,418	0	0	26,956,418	22,682,168
1909	22,356,301	26,956,418	22,682,168	7,500,000	6,570,000	722,429	34,520,290	4,990,260	0	29,530,030	24,847,704
1910	14,650,616	29,530,030	24,847,704	7,500,000	6,570,000	747,548	29,363,098	0	0	29,363,098	24,707,241
1911	15,499,729	29,363,098	24,707,241	7,500,000	6,570,000	747,548	30,045,280	515,249	0	29,530,030	24,847,704
1912	18,623,410	29,530,030	24,847,704	7,500,000	6,570,000	749,290	33,334,150	3,804,120	0	29,530,030	24,847,704
1913	14,536,373	29,530,030	24,847,704	7,500,000	6,570,000	746,368	29,250,036	0	0	29,250,036	24,612,106
1914	21,354,814	29,250,036	24,612,106	7,500,000	6,570,000	746,368	35,788,482	6,258,451	0	29,530,030	24,847,704
1915	13,623,277	29,530,030	24,847,704	7,500,000	6,570,000	736,936	28,346,371	0	0	28,346,371	23,851,728
1916	20,142,892	28,346,371	23,851,728	7,500,000	6,570,000	736,936	33,682,327	4,152,296	0	29,530,030	24,847,704
1917	22,942,804	29,530,030	24,847,704	7,500,000	6,570,000	749,290	37,653,544	8,123,514	0	29,530,030	24,847,704
1918	15,865,939	29,530,030	24,847,704	7,500,000	6,570,000	749,290	30,576,679	1,046,649	0	29,530,030	24,847,704
1919	12,651,369	29,530,030	24,847,704	7,500,000	6,570,000	726,897	27,384,502	0	0	27,384,502	23,042,374
1920	22,287,632	27,384,502	23,042,374	7,500,000	6,570,000	726,897	34,875,237	5,345,207	0	29,530,030	24,847,704
1921	22,526,781	29,530,030	24,847,704	7,500,000	6,570,000	749,290	37,237,521	7,707,491	0	29,530,030	24,847,704
1922	18,447,198	29,530,030	24,847,704	7,500,000	6,570,000	749,290	33,157,938	3,627,908	0	29,530,030	24,847,704
1923	19,024,046	29,530,030	24,847,704	7,500,000	6,570,000	749,290	33,734,786	4,204,756	0	29,530,030	24,847,704
1924	13,877,798	29,530,030	24,847,704	7,500,000	6,570,000	739,565	28,598,263	0	0	28,598,263	24,063,679
1925	14,430,701	28,598,263	24,063,679	7,500,000	6,570,000	726,027	28,232,937	0	0	28,232,937	23,756,279
1926	15,213,731	28,232,937	23,756,279	7,500,000	6,570,000	726,568	28,650,099	0	0	28,650,099	24,107,296
1927	19,539,212	28,650,099	24,107,296	7,500,000	6,570,000	740,106	33,379,205	3,849,175	0	29,530,030	24,847,704
1928	16,954,334	29,530,030	24,847,704	7,500,000	6,570,000	749,290	31,665,074	2,135,044	0	29,530,030	24,847,704
1929	21,829,585	29,530,030	24,847,704	7,500,000	6,570,000	749,290	36,540,325	7,010,295	0	29,530,030	24,847,704
1930	14,621,041	29,530,030	24,847,704	7,500,000	6,570,000	747,242	29,333,829	0	0	29,333,829	24,682,613
1931	8,474,134	29,333,829	24,682,613	7,500,000	6,570,000	679,696	23,058,267	0	0	23,058,267	19,402,113
1932	17,422,187	23,058,267	19,402,113	7,500,000	6,570,000	642,479	25,767,975	0	0	25,767,975	21,682,166
1933	12,183,500	25,767,975	21,682,166	7,500,000	6,570,000	644,346	23,237,129	0	0	23,237,129	19,552,614
1934	6,178,192	23,237,129	19,552,614	7,500,000	6,570,000	530,032	14,815,289	0	0	14,815,289	12,466,154
1935	12,630,349	14,815,289	12,466,154	7,500,000	6,570,000	422,695	12,952,943	0	0	12,952,943	10,899,105
1936	14,648,873	12,952,943	10,899,105	7,500,000	6,570,000	405,072	13,126,744	0	0	13,126,744	11,045,348
1937	14,306,056	13,126,744	11,045,348	7,500,000	6,570,000	405,121	12,957,679	0	0	12,957,679	10,903,090
1938	18,148,319	12,957,679	10,903,090	7,500,000	6,570,000	441,316	16,594,682	0	0	16,594,682	13,963,404
1939	11,164,059	16,594,682	13,963,404	7,500,000	6,570,000	444,309	13,244,432	0	0	13,244,432	11,144,375
1940	9,931,657	13,244,432	11,144,375	7,500,000	6,570,000	362,368	8,743,721	0	0	8,743,721	7,357,303
1941	20,116,678	8,743,721	7,357,303	7,500,000	6,570,000	374,594	14,415,805	0	0	14,415,805	12,130,013
1942	17,225,136	14,415,805	12,130,013	7,500,000	6,570,000	461,903	17,109,038	0	0	17,109,038	14,396,203
1943	13,731,401	17,109,038	14,396,203	7,500,000	6,570,000	481,454	16,288,986	0	0	16,288,986	13,706,179
1944	15,369,422	16,288,986	13,706,179	7,500,000	6,570,000	481,432	17,106,976	0	0	17,106,976	14,394,468
1945	14,140,528	17,106,976	14,394,468	7,500,000	6,570,000	485,637	16,691,867	0	0	16,691,867	14,045,179
1946	11,095,453	16,691,867	14,045,179	7,500,000	6,570,000	445,608	13,271,712	0	0	13,271,712	11,167,329
1947	16,439,486	13,271,712	11,167,329	7,500,000	6,570,000	430,153	15,211,045	0	0	15,211,045	12,799,159
1948	15,139,294	15,211,045	12,799,159	7,500,000	6,570,000	456,786	15,823,553	0	0	15,823,553	13,314,546
1949	16,933,584	15,823,553	13,314,546	7,500,000	6,570,000	487,974	18,199,163	0	0	18,199,163	15,313,476
1950	13,140,416	18,199,163	15,313,476	7,500,000	6,570,000	497,870	16,771,709	0	0	16,771,709	14,112,362
1951	12,505,894	16,771,709	14,112,362	7,500,000	6,570,000	461,826	14,745,777	0	0	14,745,777	12,407,664
1952	20,805,422	14,745,777	12,407,664	7,500,000	6,570,000	505,702	20,975,497	0	0	20,975,497	17,649,591
1953	11,165,419	20,975,497	17,649,591	7,500,000	6,570,000	534,824	17,536,092	0	0	17,536,092	14,755,543
1954	8,496,102	17,536,092	14,755,543	7,500,000	6,570,000	436,199	11,525,995	0	0	11,525,995	9,698,416
1955	9,413,908	11,525,995	9,698,416	7,500,000	6,570,000	321,520	6,548,383	0	0	6,548,383	5,510,062
1956	11,426,874	6,548,383	5,510,062	7,500,000	6,570,000	239,482	3,665,775	0	0	3,665,775	3,084,525
1957	21,500,963	3,665,775	3,084,525	7,500,000	6,570,000	283,989	10,812,749	0	0	10,812,749	9,098,263
1958	15,862,511	10,812,749	9,098,263	7,500,000	6,570,000	373,394	12,231,866	0	0	12,231,866	10,292,363
1959	9,598,169	12,231,866	10,292,363	7,500,000	6,570,000	338,005	7,422,030	0	0	7,422,030	6,245,181
1960	11,524,160	7,422,030	6,245,181	7,500,000	6,570,000	258,535	4,617,655	0	0	4,617,655	3,885,472
1961	10,010,259	4,617,655	3,885,472	7,500,000	6,570,000	184,963	372,950	0	0	372,950	313,815
1962	17,377,609	372,950	313,815	7,500,000	6,570,000	173,373	3,507,186	0	0	3,507,186	2,951,081
1963	8,840,900	3,507,186	2,951,081	7,500,000	6,570,000	169,481	-1,891,395	0	1,891,395	0	0
1964	10,863,586	0	0	7,500,000	6,570,000	132,876	-3,339,290	0	3,339,290	0	0
1965	19,875,027	0	0	7,500,000	6,570,000	191,465	5,613,562	0	0	5,613,562	4,723,467
1966	10,679,844	5,613,562	4,723,467	7,500,000	6,570,000	212,454	2,010,952	0	0	2,010,952	1,692,093
1967	11,670,830	2,010,952	1,692,093	7,500,000	6,570,000	153,864	-542,082	0	542,082	0	0
1968	13,739,932	0	0	7,500,000	6,570,000	132,876	-462,944	0	462,944	0	0
1969	15,272,159	0	0	7,500,000	6,570,000	143,921	1,058,238	0	0	1,058,238	890,442
1970	15,344,136	1,058,238	890,442	7,500,000	6,570,000	166,526	2,165,848	0	0	2,165,848	1,822,428
1971	15,493,659	2,165,848	1,822,428	7,500,000	6,570,000	190,952	3,398,555	0	0	3,398,555	2,859,675
1972	13,186,637	3,398,555	2,859,675	7,500,000	6,570,000	192,588	2,322,603	0	0	2,322,603	1,954,327
1973	18,650,193	2,322,603	1,954,327	7,500,000	6,570,000	226,795	6,676,001	0	0	6,676,001	5,617,444
1974	13,285,426	6,676,001	5,617,444	7,500,000	6,570,000	261,316	5,630,111	0	0	5,630,111	4,737,392
1975	17,072,661	5,630,111	4,737,392	7,500,000	6,570,000	278,829	8,353,944	0	0	8,353,944	7,029,330
1976	11,313,561	8,353,944	7,029,330	7,500,000	6,570,000	275,612	5,321,894	0	0	5,321,894	4,478,046
1977	5,551,188	5,321,894	4,478,046	7,500,000	6,570,000	188,421	-3,385,340	0	3,385,340	0	0
1978	15,335,909	0	0	7,500,000	6,570,000	144,579	1,121,329	0	0	1,121,329	943,530
1979	17,825,429	1,121,329	943,530	7,500,000	6,570,000	193,459	4,683,298	0	0	4,683,298	3,940,708
1980	17,927,076	4,683,298	3,940,708	7,500,000	6,570,000	268,094	8,272,280	0	0	8,272,280	6,960,615
1981	9,015,200	8,272,280	6,960,615	7,500,000	6,570,000	250,184	2,967,296	0	0	2,967,296	2,496,797
1982	17,489,400	2,967,296	2,496,797	7,500,000	6,570,000	228,123	6,158,572	0	0	6,158,572	5,182,060
1983	24,361,989	6,158,572	5,182,060	7,500,000	6,570,000	365,039	16,085,522	0	0	16,085,522	13,534,977
1984	25,359,376	16,085,522	13,534,977	7,500,000	6,570,000	580,418	26,794,480	0	0	26,794,480	22,545,907
1985	21,246,109	26,794,480	22,545,907	7,500,000	6,570,000	720,739	33,249,850	3,719,820	0	29,530,030	24,847,704
1986	23,013,446	29,530,030	24,847,704	7,500,000	6,570,000	749,290	37,724,186	8,194,156	0	29,530,030	24,847,704
1987	15,640,478	29,530,030	24,847,704	7,500,000	6,570,000	749,290	30,351,219	821,188	0	29,530,030	24,847,704
1988	11,456,357	29,530,030	24,847,704	7,500,000	6,570,000	714,554	26,201,833	0	0	26,201,833	22,047,231
1989	9,921,847	26,201,833	22,047,231	7,500,000	6,570,000	629,948	21,423,732	0	0	21,423,732	18,026,753
1990	9,639,803	21,423,732	18,026,753	7,500,000	6,570,000	528,326	16,465,210	0	0	16,465,210	13,854,461
1991	12,170,021	16,465,210	13,854,461	7,500,000	6,570,000	452,025	14,113,205	0	0	14,113,205	11,875,394
1992	10,895,580	14,113,205	11,875,394	7,500,000	6,570,000	390,272	10,548,513	0	0	10,548,513	8,875,925
1993	18,160,118	10,548,513	8,875,925	7,500,000	6,570,000	391,668	14,246,963	0	0	14,246,963	11,987,943
1994	11,125,503	14,246,963	11,987,943	7,500,000	6,570,000	395,410	10,907,055	0	0	10,907,055	9,177,616
1995	20,047,166	10,907,055	9,177,616	7,500,000	6,570,000	418,567	16,465,654	0	0	16,465,654	13,854,835
1996	14,502,293	16,465,654	13,854,835	7,500,000	6,570,000	476,125	16,421,822	0	0	16,421,822	13,817,953
1997	21,622,438	16,421,822	13,817,953	7,500,000	6,570,000	548,765	23,425,495	0	0	23,425,495	19,711,113
1998	16,798,378	23,425,495	19,711,113	7,500,000	6,570,000	643,622	25,510,251	0	0	25,510,251	21,465,307
1999	15,934,210	25,510,251	21,465,307	7,500,000	6,570,000	677,764	26,696,697	0	0	26,696,697	22,463,628
2000	10,646,526	26,696,697	22,463,628	7,500,000	6,570,000	647,656	22,625,567	0	0	22,625,567	19,038,023
Total									9,621,051		
Averages:											
1953-1977	13,088,628			7,500,000	6,570,000	242,490		0	384,842	4,831,696	4,065,575
1931-1977	13,594,590			7,500,000	6,570,000	353,418		0	204,703	10,253,242	8,627,472
1906-2000	15,284,742			7,500,000	6,570,000	487,445		901,250	101,274	16,949,719	14,262,146

Percentage shortage =
5.86%
3.12%
1.54%

Variables

Storage	30,167,576 af
Sedimentation Rate (Active)	24,292 af/yr
Bank Storage	4%
Adjusted Storage (2060)	29,530,030 af
UB Demand Level	6,570,000 af/yr
LB Delivery	7,500,000 af/yr

Results

Average CRSP Evap	487,445 af/yr
Total Yield w/ CRSP evap	7,057,445 af/yr

Shortage Years	**Shortage**
1963	1,891,395 af
1964	3,339,290 af
1967	542,082 af
1968	462,944 af
1977	3,385,340 af

NM allocation(w/o evap) 733,500 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,812,490 af/yr
1931-1977	6,923,418 af/yr
1906-2000	7,057,445 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Upper Basin Yield Mass Balance Analysis

Run 5 - Use CRSP Minimum Power Pools, 8.25 maf Lower Basin Delivery, No Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	33,833,590	29,151,263	8,250,000	5,720,000	725,390	37,688,221	3,854,631	0	33,833,590	29,151,263
1907	21,201,694	33,833,590	29,151,263	8,250,000	5,720,000	725,390	40,339,894	6,506,304	0	33,833,590	29,151,263
1908	12,218,817	33,833,590	29,151,263	8,250,000	5,720,000	699,302	31,383,105	0	0	31,383,105	27,039,907
1909	22,356,301	31,383,105	27,039,907	8,250,000	5,720,000	699,302	39,070,104	5,236,514	0	33,833,590	29,151,263
1910	14,650,616	33,833,590	29,151,263	8,250,000	5,720,000	724,918	33,789,288	0	0	33,789,288	29,113,092
1911	15,499,729	33,789,288	29,113,092	8,250,000	5,720,000	724,918	34,594,099	760,509	0	33,833,590	29,151,263
1912	18,623,410	33,833,590	29,151,263	8,250,000	5,720,000	725,390	37,761,610	3,928,020	0	33,833,590	29,151,263
1913	14,536,373	33,833,590	29,151,263	8,250,000	5,720,000	723,715	33,676,248	0	0	33,676,248	29,015,696
1914	21,354,814	33,676,248	29,015,696	8,250,000	5,720,000	723,715	40,337,348	6,503,758	0	33,833,590	29,151,263
1915	13,623,277	33,833,590	29,151,263	8,250,000	5,720,000	714,096	32,772,771	0	0	32,772,771	28,237,254
1916	20,142,892	32,772,771	28,237,254	8,250,000	5,720,000	714,096	38,231,566	4,397,976	0	33,833,590	29,151,263
1917	22,942,804	33,833,590	29,151,263	8,250,000	5,720,000	725,390	42,081,004	8,247,414	0	33,833,590	29,151,263
1918	15,865,939	33,833,590	29,151,263	8,250,000	5,720,000	725,390	35,004,139	1,170,549	0	33,833,590	29,151,263
1919	12,651,369	33,833,590	29,151,263	8,250,000	5,720,000	703,858	31,811,100	0	0	31,811,100	27,408,672
1920	22,287,632	31,811,100	27,408,672	8,250,000	5,720,000	703,858	39,424,874	5,591,284	0	33,833,590	29,151,263
1921	22,526,781	33,833,590	29,151,263	8,250,000	5,720,000	725,390	41,664,981	7,831,391	0	33,833,590	29,151,263
1922	18,447,198	33,833,590	29,151,263	8,250,000	5,720,000	725,390	37,585,398	3,751,808	0	33,833,590	29,151,263
1923	19,024,046	33,833,590	29,151,263	8,250,000	5,720,000	725,390	38,162,246	4,328,656	0	33,833,590	29,151,263
1924	13,877,798	33,833,590	29,151,263	8,250,000	5,720,000	716,777	33,024,611	0	0	33,024,611	28,454,241
1925	14,430,701	33,024,611	28,454,241	8,250,000	5,720,000	705,558	32,779,753	0	0	32,779,753	28,243,270
1926	15,213,731	32,779,753	28,243,270	8,250,000	5,720,000	708,648	33,314,836	0	0	33,314,836	28,704,301
1927	19,539,212	33,314,836	28,704,301	8,250,000	5,720,000	719,867	38,164,181	4,330,591	0	33,833,590	29,151,263
1928	16,954,334	33,833,590	29,151,263	8,250,000	5,720,000	725,390	36,092,534	2,258,944	0	33,833,590	29,151,263
1929	21,829,585	33,833,590	29,151,263	8,250,000	5,720,000	725,390	40,967,785	7,134,195	0	33,833,590	29,151,263
1930	14,621,041	33,833,590	29,151,263	8,250,000	5,720,000	724,606	33,760,025	0	0	33,760,025	29,087,879
1931	8,474,134	33,760,025	29,087,879	8,250,000	5,720,000	658,307	27,605,852	0	0	27,605,852	23,785,399
1932	17,422,187	27,605,852	23,785,399	8,250,000	5,720,000	622,911	30,435,128	0	0	30,435,128	26,223,124
1933	12,183,500	30,435,128	26,223,124	8,250,000	5,720,000	627,333	28,021,294	0	0	28,021,294	24,143,347
1934	6,178,192	28,021,294	24,143,347	8,250,000	5,720,000	513,222	19,716,264	0	0	19,716,264	16,987,674
1935	12,630,349	19,716,264	16,987,674	8,250,000	5,720,000	406,222	17,970,391	0	0	17,970,391	15,483,417
1936	14,648,873	17,970,391	15,483,417	8,250,000	5,720,000	390,704	18,258,560	0	0	18,258,560	15,731,706
1937	14,306,056	18,258,560	15,731,706	8,250,000	5,720,000	393,164	18,201,452	0	0	18,201,452	15,682,501
1938	18,148,319	18,201,452	15,682,501	8,250,000	5,720,000	432,434	21,947,337	0	0	21,947,337	18,909,983
1939	11,164,059	21,947,337	18,909,983	8,250,000	5,720,000	437,780	18,703,617	0	0	18,703,617	16,115,170
1940	9,931,657	18,703,617	16,115,170	8,250,000	5,720,000	356,461	14,308,812	0	0	14,308,812	12,328,575
1941	20,116,678	14,308,812	12,328,575	8,250,000	5,720,000	371,160	20,084,330	0	0	20,084,330	17,304,802
1942	17,225,136	20,084,330	17,304,802	8,250,000	5,720,000	462,377	22,877,090	0	0	22,877,090	19,711,064
1943	13,731,401	22,877,090	19,711,064	8,250,000	5,720,000	484,411	22,154,080	0	0	22,154,080	19,088,114
1944	15,369,422	22,154,080	19,088,114	8,250,000	5,720,000	486,433	23,067,069	0	0	23,067,069	19,874,751
1945	14,140,528	23,067,069	19,874,751	8,250,000	5,720,000	492,723	22,744,874	0	0	22,744,874	19,597,146
1946	11,095,453	22,744,874	19,597,146	8,250,000	5,720,000	453,859	19,416,468	0	0	19,416,468	16,729,368
1947	16,439,486	19,416,468	16,729,368	8,250,000	5,720,000	440,031	21,445,923	0	0	21,445,923	18,477,961
1948	15,139,294	21,445,923	18,477,961	8,250,000	5,720,000	469,090	22,146,127	0	0	22,146,127	19,081,262
1949	16,933,584	22,146,127	19,081,262	8,250,000	5,720,000	502,742	24,606,969	0	0	24,606,969	21,201,541
1950	13,140,416	24,606,969	21,201,541	8,250,000	5,720,000	514,629	23,262,756	0	0	23,262,756	20,043,357
1951	12,505,894	23,262,756	20,043,357	8,250,000	5,720,000	479,627	21,319,023	0	0	21,319,023	18,368,623
1952	20,805,422	21,319,023	18,368,623	8,250,000	5,720,000	526,102	27,628,343	0	0	27,628,343	23,804,778
1953	11,165,419	27,628,343	23,804,778	8,250,000	5,720,000	557,478	24,266,285	0	0	24,266,285	20,908,004
1954	8,496,102	24,266,285	20,908,004	8,250,000	5,720,000	458,530	18,333,856	0	0	18,333,856	15,796,582
1955	9,413,908	18,333,856	15,796,582	8,250,000	5,720,000	343,218	13,434,547	0	0	13,434,547	11,575,301
1956	11,426,874	13,434,547	11,575,301	8,250,000	5,720,000	261,206	10,630,214	0	0	10,630,214	9,159,069
1957	21,500,963	10,630,214	9,159,069	8,250,000	5,720,000	308,243	17,852,934	0	0	17,852,934	15,382,216
1958	15,862,511	17,852,934	15,382,216	8,250,000	5,720,000	401,013	19,344,432	0	0	19,344,432	16,667,301
1959	9,598,169	19,344,432	16,667,301	8,250,000	5,720,000	366,449	14,606,152	0	0	14,606,152	12,584,765
1960	11,524,160	14,606,152	12,584,765	8,250,000	5,720,000	286,914	11,873,398	0	0	11,873,398	10,230,205
1961	10,010,259	11,873,398	10,230,205	8,250,000	5,720,000	213,395	7,700,263	0	0	7,700,263	6,634,601
1962	17,377,609	7,700,263	6,634,601	8,250,000	5,720,000	203,083	10,904,789	0	0	10,904,789	9,395,644
1963	8,840,900	10,904,789	9,395,644	8,250,000	5,720,000	180,671	5,595,018	0	0	5,595,018	4,820,707
1964	10,863,586	5,595,018	4,820,707	8,250,000	5,720,000	90,114	2,398,489	0	0	2,398,489	2,066,556
1965	19,875,027	2,398,489	2,066,556	8,250,000	5,720,000	117,696	8,185,821	0	0	8,185,821	7,052,962
1966	10,679,844	8,185,821	7,052,962	8,250,000	5,720,000	142,760	4,752,904	0	0	4,752,904	4,095,136
1967	11,670,830	4,752,904	4,095,136	8,250,000	5,720,000	80,877	2,372,858	0	0	2,372,858	2,044,471
1968	13,739,932	2,372,858	2,044,471	8,250,000	5,720,000	52,531	2,090,259	0	0	2,090,259	1,800,982
1969	15,272,159	2,090,259	1,800,982	8,250,000	5,720,000	62,717	3,329,701	0	0	3,329,701	2,868,894
1970	15,344,136	3,329,701	2,868,894	8,250,000	5,720,000	89,587	4,614,250	0	0	4,614,250	3,975,671
1971	15,493,659	4,614,250	3,975,671	8,250,000	5,720,000	118,224	6,019,685	0	0	6,019,685	5,186,604
1972	13,186,637	6,019,685	5,186,604	8,250,000	5,720,000	123,531	5,112,790	0	0	5,112,790	4,405,217
1973	18,650,193	5,112,790	4,405,217	8,250,000	5,720,000	161,977	9,631,006	0	0	9,631,006	8,298,144
1974	13,285,426	9,631,006	8,298,144	8,250,000	5,720,000	200,653	8,745,780	0	0	8,745,780	7,535,427
1975	17,072,661	8,745,780	7,535,427	8,250,000	5,720,000	221,897	11,626,544	0	0	11,626,544	10,017,513
1976	11,313,561	11,626,544	10,017,513	8,250,000	5,720,000	221,923	8,748,183	0	0	8,748,183	7,537,497
1977	5,551,188	8,748,183	7,537,497	8,250,000	5,720,000	100,584	228,786	0	0	228,786	197,124
1978	15,335,909	228,786	197,124	8,250,000	5,720,000	24,172	1,570,522	0	0	1,570,522	1,353,173
1979	17,825,429	1,570,522	1,353,173	8,250,000	5,720,000	78,663	5,347,288	0	0	5,347,288	4,607,262
1980	17,927,076	5,347,288	4,607,262	8,250,000	5,720,000	159,300	9,145,065	0	0	9,145,065	7,879,453
1981	9,015,200	9,145,065	7,879,453	8,250,000	5,720,000	145,434	4,044,830	0	0	4,044,830	3,485,055
1982	17,489,400	4,044,830	3,485,055	8,250,000	5,720,000	127,250	7,436,980	0	0	7,436,980	6,407,755
1983	24,361,989	7,436,980	6,407,755	8,250,000	5,720,000	271,108	17,557,861	0	0	17,557,861	15,127,979
1984	25,359,376	17,557,861	15,127,979	8,250,000	5,720,000	494,834	28,452,403	0	0	28,452,403	24,514,794
1985	21,246,109	28,452,403	24,514,794	8,250,000	5,720,000	668,102	35,060,409	1,226,819	0	33,833,590	29,151,263
1986	23,013,446	33,833,590	29,151,263	8,250,000	5,720,000	725,390	42,151,647	8,318,057	0	33,833,590	29,151,263
1987	15,640,478	33,833,590	29,151,263	8,250,000	5,720,000	725,390	34,778,679	945,089	0	33,833,590	29,151,263
1988	11,456,357	33,833,590	29,151,263	8,250,000	5,720,000	691,271	30,628,676	0	0	30,628,676	26,389,886
1989	9,921,847	30,628,676	26,389,886	8,250,000	5,720,000	607,588	25,972,935	0	0	25,972,935	22,378,466
1990	9,639,803	25,972,935	22,378,466	8,250,000	5,720,000	506,532	21,136,206	0	0	21,136,206	18,211,106
1991	12,170,021	21,136,206	18,211,106	8,250,000	5,720,000	431,288	18,904,938	0	0	18,904,938	16,288,630
1992	10,895,580	18,904,938	16,288,630	8,250,000	5,720,000	370,856	15,459,662	0	0	15,459,662	13,320,155
1993	18,160,118	15,459,662	13,320,155	8,250,000	5,720,000	374,796	19,274,984	0	0	19,274,984	16,607,464
1994	11,125,503	19,274,984	16,607,464	8,250,000	5,720,000	381,074	16,049,413	0	0	16,049,413	13,828,289
1995	20,047,166	16,049,413	13,828,289	8,250,000	5,720,000	407,098	21,719,481	0	0	21,719,481	18,713,660
1996	14,502,293	21,719,481	18,713,660	8,250,000	5,720,000	468,143	21,783,631	0	0	21,783,631	18,768,932
1997	21,622,438	21,783,631	18,768,932	8,250,000	5,720,000	544,496	28,891,573	0	0	28,891,573	24,893,185
1998	16,798,378	28,891,573	24,893,185	8,250,000	5,720,000	643,427	31,076,524	0	0	31,076,524	26,775,755
1999	15,934,210	31,076,524	26,775,755	8,250,000	5,720,000	680,355	32,360,379	0	0	32,360,379	27,881,934
2000	10,646,526	32,360,379	27,881,934	8,250,000	5,720,000	651,703	28,385,202	0	0	28,385,202	24,456,893
Total									0		
Averages:											
1953-1977	13,088,628			8,250,000	5,720,000	214,611		0	0	9,295,958	8,009,464
1931-1977	13,594,590			8,250,000	5,720,000	338,021		0	0	15,283,419	13,168,303
1906-2000	15,284,742			8,250,000	5,720,000	463,436		908,658	0	21,501,781	18,526,088

Variables

Storage	35,233,298 af
Sedimentation Rate (Active)	37,000 af/yr
Bank Storage	4%
Adjusted Storage (2060)	33,833,590 af
UB Demand Level	5,720,000 af/yr
LB Delivery	8,250,000 af/yr

Results

Average CRSP Evap	463,436 af/yr
Total Yield w/ CRSP evap	6,183,436 af/yr

Shortage Years	**Shortage**
1963	0 af
1964	0 af
1967	0 af
1968	0 af
1977	0 af

NM allocation (w/o evap) 637,875 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	5,934,611 af/yr
1931-1977	6,058,021 af/yr
1906-2000	6,183,436 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =
0.00%
0.00%
0.00%

Upper Basin Yield Mass Balance Analysis

Run 6 - Use CRSP Minimum Power Pools, 8.25 maf Lower Basin Delivery, 6% Overall Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	33,833,590	29,151,263	8,250,000	5,980,000	725,390	37,428,221	3,594,631	0	33,833,590	29,151,263
1907	21,201,694	33,833,590	29,151,263	8,250,000	5,980,000	725,390	40,079,894	6,246,304	0	33,833,590	29,151,263
1908	12,218,817	33,833,590	29,151,263	8,250,000	5,980,000	696,563	31,125,844	0	0	31,125,844	26,818,249
1909	22,356,301	31,125,844	26,818,249	8,250,000	5,980,000	696,563	38,555,581	4,721,991	0	33,833,590	29,151,263
1910	14,650,616	33,833,590	29,151,263	8,250,000	5,980,000	722,179	33,532,027	0	0	33,532,027	28,891,434
1911	15,499,729	33,532,027	28,891,434	8,250,000	5,980,000	722,179	34,079,577	245,987	0	33,833,590	29,151,263
1912	18,623,410	33,833,590	29,151,263	8,250,000	5,980,000	725,390	37,501,610	3,668,020	0	33,833,590	29,151,263
1913	14,536,373	33,833,590	29,151,263	8,250,000	5,980,000	720,976	33,418,987	0	0	33,418,987	28,794,038
1914	21,354,814	33,418,987	28,794,038	8,250,000	5,980,000	720,976	39,822,825	5,989,235	0	33,833,590	29,151,263
1915	13,623,277	33,833,590	29,151,263	8,250,000	5,980,000	711,358	32,515,509	0	0	32,515,509	28,015,595
1916	20,142,892	32,515,509	28,015,595	8,250,000	5,980,000	711,358	37,717,044	3,883,454	0	33,833,590	29,151,263
1917	22,942,804	33,833,590	29,151,263	8,250,000	5,980,000	725,390	41,821,004	7,987,414	0	33,833,590	29,151,263
1918	15,865,939	33,833,590	29,151,263	8,250,000	5,980,000	725,390	34,744,139	910,549	0	33,833,590	29,151,263
1919	12,651,369	33,833,590	29,151,263	8,250,000	5,980,000	701,120	31,553,839	0	0	31,553,839	27,187,013
1920	22,287,632	31,553,839	27,187,013	8,250,000	5,980,000	701,120	38,910,351	5,076,762	0	33,833,590	29,151,263
1921	22,526,781	33,833,590	29,151,263	8,250,000	5,980,000	725,390	41,404,981	7,571,391	0	33,833,590	29,151,263
1922	18,447,198	33,833,590	29,151,263	8,250,000	5,980,000	725,390	37,325,398	3,491,808	0	33,833,590	29,151,263
1923	19,024,046	33,833,590	29,151,263	8,250,000	5,980,000	725,390	37,902,246	4,068,656	0	33,833,590	29,151,263
1924	13,877,798	33,833,590	29,151,263	8,250,000	5,980,000	714,039	32,767,349	0	0	32,767,349	28,232,583
1925	14,430,701	32,767,349	28,232,583	8,250,000	5,980,000	697,400	32,270,651	0	0	32,270,651	27,804,623
1926	15,213,731	32,270,651	27,804,623	8,250,000	5,980,000	695,184	32,559,198	0	0	32,559,198	28,053,238
1927	19,539,212	32,559,198	28,053,238	8,250,000	5,980,000	711,823	37,156,587	3,322,997	0	33,833,590	29,151,263
1928	16,954,334	33,833,590	29,151,263	8,250,000	5,980,000	725,390	35,832,534	1,998,944	0	33,833,590	29,151,263
1929	21,829,585	33,833,590	29,151,263	8,250,000	5,980,000	725,390	40,707,785	6,874,195	0	33,833,590	29,151,263
1930	14,621,041	33,833,590	29,151,263	8,250,000	5,980,000	721,868	33,502,763	0	0	33,502,763	28,866,220
1931	8,474,134	33,502,763	28,866,220	8,250,000	5,980,000	650,148	27,096,749	0	0	27,096,749	23,346,753
1932	17,422,187	27,096,749	23,346,753	8,250,000	5,980,000	609,447	29,679,489	0	0	29,679,489	25,572,060
1933	12,183,500	29,679,489	25,572,060	8,250,000	5,980,000	608,675	27,024,314	0	0	27,024,314	23,284,342
1934	6,178,192	27,024,314	23,284,342	8,250,000	5,980,000	489,480	18,483,026	0	0	18,483,026	15,925,107
1935	12,630,349	18,483,026	15,925,107	8,250,000	5,980,000	377,502	16,505,872	0	0	16,505,872	14,221,578
1936	14,648,873	16,505,872	14,221,578	8,250,000	5,980,000	357,112	16,567,634	0	0	16,567,634	14,274,792
1937	14,306,056	16,567,634	14,274,792	8,250,000	5,980,000	354,802	16,288,888	0	0	16,288,888	14,034,623
1938	18,148,319	16,288,888	14,034,623	8,250,000	5,980,000	389,402	19,817,805	0	0	19,817,805	17,075,162
1939	11,164,059	19,817,805	17,075,162	8,250,000	5,980,000	390,177	16,361,687	0	0	16,361,687	14,097,346
1940	9,931,657	16,361,687	14,097,346	8,250,000	5,980,000	304,384	11,758,959	0	0	11,758,959	10,131,603
1941	20,116,678	11,758,959	10,131,603	8,250,000	5,980,000	314,703	17,330,935	0	0	17,330,935	14,932,457
1942	17,225,136	17,330,935	14,932,457	8,250,000	5,980,000	401,631	19,924,440	0	0	19,924,440	17,167,040
1943	13,731,401	19,924,440	17,167,040	8,250,000	5,980,000	419,467	19,006,373	0	0	19,006,373	16,376,027
1944	15,369,422	19,006,373	16,376,027	8,250,000	5,980,000	417,381	19,728,415	0	0	19,728,415	16,998,143
1945	14,140,528	19,728,415	16,998,143	8,250,000	5,980,000	419,647	19,219,295	0	0	19,219,295	16,559,482
1946	11,095,453	19,219,295	16,559,482	8,250,000	5,980,000	376,846	15,707,903	0	0	15,707,903	13,534,041
1947	16,439,486	15,707,903	13,534,041	8,250,000	5,980,000	359,162	17,558,227	0	0	17,558,227	15,128,294
1948	15,139,294	17,558,227	15,128,294	8,250,000	5,980,000	384,448	18,083,073	0	0	18,083,073	15,580,505
1949	16,933,584	18,083,073	15,580,505	8,250,000	5,980,000	414,405	20,372,251	0	0	20,372,251	17,552,877
1950	13,140,416	20,372,251	17,552,877	8,250,000	5,980,000	422,676	18,859,991	0	0	18,859,991	16,249,903
1951	12,505,894	18,859,991	16,249,903	8,250,000	5,980,000	384,133	16,751,752	0	0	16,751,752	14,433,429
1952	20,805,422	16,751,752	14,433,429	8,250,000	5,980,000	427,143	22,900,031	0	0	22,900,031	19,730,831
1953	11,165,419	22,900,031	19,730,831	8,250,000	5,980,000	455,126	19,380,324	0	0	19,380,324	16,698,226
1954	8,496,102	19,380,324	16,698,226	8,250,000	5,980,000	352,857	13,293,569	0	0	13,293,569	11,453,834
1955	9,413,908	13,293,569	11,453,834	8,250,000	5,980,000	234,293	8,243,183	0	0	8,243,183	7,102,386
1956	11,426,874	8,243,183	7,102,386	8,250,000	5,980,000	149,099	5,290,958	0	0	5,290,958	4,558,728
1957	21,500,963	5,290,958	4,558,728	8,250,000	5,980,000	193,021	12,368,901	0	0	12,368,901	10,657,133
1958	15,862,511	12,368,901	10,657,133	8,250,000	5,980,000	282,741	13,718,671	0	0	13,718,671	11,820,105
1959	9,598,169	13,718,671	11,820,105	8,250,000	5,980,000	245,190	8,841,650	0	0	8,841,650	7,618,029
1960	11,524,160	8,841,650	7,618,029	8,250,000	5,980,000	162,732	5,973,078	0	0	5,973,078	5,146,447
1961	10,010,259	5,973,078	5,146,447	8,250,000	5,980,000	86,352	1,666,985	0	0	1,666,985	1,436,286
1962	17,377,609	1,666,985	1,436,286	8,250,000	5,980,000	73,239	4,741,355	0	0	4,741,355	4,085,186
1963	8,840,900	4,741,355	4,085,186	8,250,000	5,980,000	55,493	-703,237	0	703,237	0	0
1964	10,863,586	0	0	8,250,000	5,980,000	5,017	-3,371,431	0	3,371,431	0	0
1965	19,875,027	0	0	8,250,000	5,980,000	64,427	5,580,600	0	0	5,580,600	4,808,285
1966	10,679,844	5,580,600	4,808,285	8,250,000	5,980,000	85,136	1,945,307	0	0	1,945,307	1,676,091
1967	11,670,830	1,945,307	1,676,091	8,250,000	5,980,000	25,726	-639,589	0	639,589	0	0
1968	13,739,932	0	0	8,250,000	5,980,000	5,017	-495,085	0	495,085	0	0
1969	15,272,159	0	0	8,250,000	5,980,000	15,942	1,026,217	0	0	1,026,217	884,196
1970	15,344,136	1,026,217	884,196	8,250,000	5,980,000	38,320	2,102,033	0	0	2,102,033	1,811,127
1971	15,493,659	2,102,033	1,811,127	8,250,000	5,980,000	62,559	3,303,132	0	0	3,303,132	2,846,003
1972	13,186,637	3,303,132	2,846,003	8,250,000	5,980,000	63,562	2,196,207	0	0	2,196,207	1,892,268
1973	18,650,193	2,196,207	1,892,268	8,250,000	5,980,000	97,793	6,518,607	0	0	6,518,607	5,616,478
1974	13,285,426	6,518,607	5,616,478	8,250,000	5,980,000	132,344	5,441,689	0	0	5,441,689	4,688,598
1975	17,072,661	5,441,689	4,688,598	8,250,000	5,980,000	149,550	8,134,800	0	0	8,134,800	7,009,002
1976	11,313,561	8,134,800	7,009,002	8,250,000	5,980,000	145,622	5,072,739	0	0	5,072,739	4,370,709
1977	5,551,188	5,072,739	4,370,709	8,250,000	5,980,000	59,020	-3,665,093	0	3,665,093	0	0
1978	15,335,909	0	0	8,250,000	5,980,000	16,613	1,089,295	0	0	1,089,295	938,544
1979	17,825,429	1,089,295	938,544	8,250,000	5,980,000	65,786	4,618,938	0	0	4,618,938	3,979,710
1980	17,927,076	4,618,938	3,979,710	8,250,000	5,980,000	141,217	8,174,797	0	0	8,174,797	7,043,464
1981	9,015,200	8,174,797	7,043,464	8,250,000	5,980,000	122,255	2,837,743	0	0	2,837,743	2,445,019
1982	17,489,400	2,837,743	2,445,019	8,250,000	5,980,000	99,081	5,998,061	0	0	5,998,061	5,167,972
1983	24,361,989	5,998,061	5,167,972	8,250,000	5,980,000	238,055	15,891,995	0	0	15,891,995	13,692,657
1984	25,359,376	15,891,995	13,692,657	8,250,000	5,980,000	457,000	26,564,372	0	0	26,564,372	22,888,053
1985	21,246,109	26,564,372	22,888,053	8,250,000	5,980,000	638,511	32,941,970	0	0	32,941,970	28,383,037
1986	23,013,446	32,941,970	28,383,037	8,250,000	5,980,000	715,898	41,009,518	7,175,928	0	33,833,590	29,151,263
1987	15,640,478	33,833,590	29,151,263	8,250,000	5,980,000	725,390	34,518,679	685,089	0	33,833,590	29,151,263
1988	11,456,357	33,833,590	29,151,263	8,250,000	5,980,000	688,532	30,371,415	0	0	30,371,415	26,168,228
1989	9,921,847	30,371,415	26,168,228	8,250,000	5,980,000	599,429	25,463,832	0	0	25,463,832	21,939,820
1990	9,639,803	25,463,832	21,939,820	8,250,000	5,980,000	493,068	20,380,567	0	0	20,380,567	17,560,042
1991	12,170,021	20,380,567	17,560,042	8,250,000	5,980,000	412,630	17,907,958	0	0	17,907,958	15,429,625
1992	10,895,580	17,907,958	15,429,625	8,250,000	5,980,000	347,114	14,226,424	0	0	14,226,424	12,257,589
1993	18,160,118	14,226,424	12,257,589	8,250,000	5,980,000	346,076	17,810,466	0	0	17,810,466	15,345,625
1994	11,125,503	17,810,466	15,345,625	8,250,000	5,980,000	347,482	14,358,487	0	0	14,358,487	12,371,375
1995	20,047,166	14,358,487	12,371,375	8,250,000	5,980,000	368,736	19,806,917	0	0	19,806,917	17,065,781
1996	14,502,293	19,806,917	17,065,781	8,250,000	5,980,000	425,112	19,654,098	0	0	19,654,098	16,934,112
1997	21,622,438	19,654,098	16,934,112	8,250,000	5,980,000	496,894	26,549,643	0	0	26,549,643	22,875,362
1998	16,798,378	26,549,643	22,875,362	8,250,000	5,980,000	591,349	28,526,671	0	0	28,526,671	24,578,784
1999	15,934,210	28,526,671	24,578,784	8,250,000	5,980,000	623,897	29,606,984	0	0	29,606,984	25,509,589
2000	10,646,526	29,606,984	25,509,589	8,250,000	5,980,000	590,958	25,432,552	0	0	25,432,552	21,912,869
Total									8,874,436		
Averages:											
1953-1977	13,088,628			8,250,000	5,980,000	129,607		0	354,977	5,393,600	4,647,165
1931-1977	13,594,590			8,250,000	5,980,000	266,233		0	188,818	11,912,066	10,263,521
1906-2000	15,284,742			8,250,000	5,980,000	420,659		815,930	93,415	19,477,169	16,781,668

Variables

Storage	35,233,298 af
Sedimentation Rate (Active)	37,000 af/yr
Bank Storage	4%
Adjusted Storage (2060)	33,833,590 af
UB Demand Level	5,980,000 af/yr
LB Delivery	8,250,000 af/yr

Results

Average CRSP Evap	420,659 af/yr
Total Yield w/ CRSP evap	6,400,659 af/yr

Shortage Years	**Shortage**
1963	703,237 af
1964	3,371,431 af
1967	639,589 af
1968	495,085 af
1977	3,665,093 af

NM allocation (w/o evap) 667,125 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,109,607 af/yr
1931-1977	6,246,233 af/yr
1906-2000	6,400,659 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	5.94%
1931-1977	3.16%
1906-2000	1.56%

Upper Basin Yield Mass Balance Analysis

Run 7 - Use CRSP Minimum Power Pools, 7.50 maf Lower Basin Delivery, No Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	33,833,590	29,151,263	7,500,000	6,470,000	725,390	37,688,221	3,854,631	0	33,833,590	29,151,263
1907	21,201,694	33,833,590	29,151,263	7,500,000	6,470,000	725,390	40,339,894	6,506,304	0	33,833,590	29,151,263
1908	12,218,817	33,833,590	29,151,263	7,500,000	6,470,000	699,302	31,383,105	0	0	31,383,105	27,039,907
1909	22,356,301	31,383,105	27,039,907	7,500,000	6,470,000	699,302	39,070,104	5,236,514	0	33,833,590	29,151,263
1910	14,650,616	33,833,590	29,151,263	7,500,000	6,470,000	724,918	33,789,288	0	0	33,789,288	29,113,092
1911	15,499,729	33,789,288	29,113,092	7,500,000	6,470,000	724,918	34,594,099	760,509	0	33,833,590	29,151,263
1912	18,623,410	33,833,590	29,151,263	7,500,000	6,470,000	725,390	37,761,610	3,928,020	0	33,833,590	29,151,263
1913	14,536,373	33,833,590	29,151,263	7,500,000	6,470,000	723,715	33,676,248	0	0	33,676,248	29,015,696
1914	21,354,814	33,676,248	29,015,696	7,500,000	6,470,000	723,715	40,337,348	6,503,758	0	33,833,590	29,151,263
1915	13,623,277	33,833,590	29,151,263	7,500,000	6,470,000	714,096	32,772,771	0	0	32,772,771	28,237,254
1916	20,142,892	32,772,771	28,237,254	7,500,000	6,470,000	714,096	38,231,566	4,397,976	0	33,833,590	29,151,263
1917	22,942,804	33,833,590	29,151,263	7,500,000	6,470,000	725,390	42,081,004	8,247,414	0	33,833,590	29,151,263
1918	15,865,939	33,833,590	29,151,263	7,500,000	6,470,000	725,390	35,004,139	1,170,549	0	33,833,590	29,151,263
1919	12,651,369	33,833,590	29,151,263	7,500,000	6,470,000	703,858	31,811,100	0	0	31,811,100	27,408,672
1920	22,287,632	31,811,100	27,408,672	7,500,000	6,470,000	703,858	39,424,874	5,591,284	0	33,833,590	29,151,263
1921	22,526,781	33,833,590	29,151,263	7,500,000	6,470,000	725,390	41,664,981	7,831,391	0	33,833,590	29,151,263
1922	18,447,198	33,833,590	29,151,263	7,500,000	6,470,000	725,390	37,585,398	3,751,808	0	33,833,590	29,151,263
1923	19,024,046	33,833,590	29,151,263	7,500,000	6,470,000	725,390	38,162,246	4,328,656	0	33,833,590	29,151,263
1924	13,877,798	33,833,590	29,151,263	7,500,000	6,470,000	716,777	33,024,611	0	0	33,024,611	28,454,241
1925	14,430,701	33,024,611	28,454,241	7,500,000	6,470,000	705,558	32,779,753	0	0	32,779,753	28,243,270
1926	15,213,731	32,779,753	28,243,270	7,500,000	6,470,000	708,648	33,314,836	0	0	33,314,836	28,704,301
1927	19,539,212	33,314,836	28,704,301	7,500,000	6,470,000	719,867	38,164,181	4,330,591	0	33,833,590	29,151,263
1928	16,954,334	33,833,590	29,151,263	7,500,000	6,470,000	725,390	36,092,534	2,258,944	0	33,833,590	29,151,263
1929	21,829,585	33,833,590	29,151,263	7,500,000	6,470,000	725,390	40,967,785	7,134,195	0	33,833,590	29,151,263
1930	14,621,041	33,833,590	29,151,263	7,500,000	6,470,000	724,606	33,760,025	0	0	33,760,025	29,087,879
1931	8,474,134	33,760,025	29,087,879	7,500,000	6,470,000	658,307	27,605,852	0	0	27,605,852	23,785,399
1932	17,422,187	27,605,852	23,785,399	7,500,000	6,470,000	622,911	30,435,128	0	0	30,435,128	26,223,124
1933	12,183,500	30,435,128	26,223,124	7,500,000	6,470,000	627,333	28,021,294	0	0	28,021,294	24,143,347
1934	6,178,192	28,021,294	24,143,347	7,500,000	6,470,000	513,222	19,716,264	0	0	19,716,264	16,987,674
1935	12,630,349	19,716,264	16,987,674	7,500,000	6,470,000	406,222	17,970,391	0	0	17,970,391	15,483,417
1936	14,648,873	17,970,391	15,483,417	7,500,000	6,470,000	390,704	18,258,560	0	0	18,258,560	15,731,706
1937	14,306,056	18,258,560	15,731,706	7,500,000	6,470,000	393,164	18,201,452	0	0	18,201,452	15,682,501
1938	18,148,319	18,201,452	15,682,501	7,500,000	6,470,000	432,434	21,947,337	0	0	21,947,337	18,909,983
1939	11,164,059	21,947,337	18,909,983	7,500,000	6,470,000	437,780	18,703,617	0	0	18,703,617	16,115,170
1940	9,931,657	18,703,617	16,115,170	7,500,000	6,470,000	356,461	14,308,812	0	0	14,308,812	12,328,575
1941	20,116,678	14,308,812	12,328,575	7,500,000	6,470,000	371,160	20,084,330	0	0	20,084,330	17,304,802
1942	17,225,136	20,084,330	17,304,802	7,500,000	6,470,000	462,377	22,877,090	0	0	22,877,090	19,711,064
1943	13,731,401	22,877,090	19,711,064	7,500,000	6,470,000	484,411	22,154,080	0	0	22,154,080	19,088,114
1944	15,369,422	22,154,080	19,088,114	7,500,000	6,470,000	486,433	23,067,069	0	0	23,067,069	19,874,751
1945	14,140,528	23,067,069	19,874,751	7,500,000	6,470,000	492,723	22,744,874	0	0	22,744,874	19,597,146
1946	11,095,453	22,744,874	19,597,146	7,500,000	6,470,000	453,859	19,416,468	0	0	19,416,468	16,729,368
1947	16,439,486	19,416,468	16,729,368	7,500,000	6,470,000	440,031	21,445,923	0	0	21,445,923	18,477,961
1948	15,139,294	21,445,923	18,477,961	7,500,000	6,470,000	469,090	22,146,127	0	0	22,146,127	19,081,262
1949	16,933,584	22,146,127	19,081,262	7,500,000	6,470,000	502,742	24,606,969	0	0	24,606,969	21,201,541
1950	13,140,416	24,606,969	21,201,541	7,500,000	6,470,000	514,629	23,262,756	0	0	23,262,756	20,043,357
1951	12,505,894	23,262,756	20,043,357	7,500,000	6,470,000	479,627	21,319,023	0	0	21,319,023	18,368,623
1952	20,805,422	21,319,023	18,368,623	7,500,000	6,470,000	526,102	27,628,343	0	0	27,628,343	23,804,778
1953	11,165,419	27,628,343	23,804,778	7,500,000	6,470,000	557,478	24,266,285	0	0	24,266,285	20,908,004
1954	8,496,102	24,266,285	20,908,004	7,500,000	6,470,000	458,530	18,333,856	0	0	18,333,856	15,796,582
1955	9,413,908	18,333,856	15,796,582	7,500,000	6,470,000	343,218	13,434,547	0	0	13,434,547	11,575,301
1956	11,426,874	13,434,547	11,575,301	7,500,000	6,470,000	261,206	10,630,214	0	0	10,630,214	9,159,069
1957	21,500,963	10,630,214	9,159,069	7,500,000	6,470,000	308,243	17,852,934	0	0	17,852,934	15,382,216
1958	15,862,511	17,852,934	15,382,216	7,500,000	6,470,000	401,013	19,344,432	0	0	19,344,432	16,667,301
1959	9,598,169	19,344,432	16,667,301	7,500,000	6,470,000	366,449	14,606,152	0	0	14,606,152	12,584,765
1960	11,524,160	14,606,152	12,584,765	7,500,000	6,470,000	286,914	11,873,398	0	0	11,873,398	10,230,205
1961	10,010,259	11,873,398	10,230,205	7,500,000	6,470,000	213,395	7,700,263	0	0	7,700,263	6,634,601
1962	17,377,609	7,700,263	6,634,601	7,500,000	6,470,000	203,083	10,904,789	0	0	10,904,789	9,395,644
1963	8,840,900	10,904,789	9,395,644	7,500,000	6,470,000	180,671	5,595,018	0	0	5,595,018	4,820,707
1964	10,863,586	5,595,018	4,820,707	7,500,000	6,470,000	90,114	2,398,489	0	0	2,398,489	2,066,556
1965	19,875,027	2,398,489	2,066,556	7,500,000	6,470,000	117,696	8,185,821	0	0	8,185,821	7,052,962
1966	10,679,844	8,185,821	7,052,962	7,500,000	6,470,000	142,760	4,752,904	0	0	4,752,904	4,095,136
1967	11,670,830	4,752,904	4,095,136	7,500,000	6,470,000	80,877	2,372,858	0	0	2,372,858	2,044,471
1968	13,739,932	2,372,858	2,044,471	7,500,000	6,470,000	52,531	2,090,259	0	0	2,090,259	1,800,982
1969	15,272,159	2,090,259	1,800,982	7,500,000	6,470,000	62,717	3,329,701	0	0	3,329,701	2,868,894
1970	15,344,136	3,329,701	2,868,894	7,500,000	6,470,000	89,587	4,614,250	0	0	4,614,250	3,975,671
1971	15,493,659	4,614,250	3,975,671	7,500,000	6,470,000	118,224	6,019,685	0	0	6,019,685	5,186,604
1972	13,186,637	6,019,685	5,186,604	7,500,000	6,470,000	123,531	5,112,790	0	0	5,112,790	4,405,217
1973	18,650,193	5,112,790	4,405,217	7,500,000	6,470,000	161,977	9,631,006	0	0	9,631,006	8,298,144
1974	13,285,426	9,631,006	8,298,144	7,500,000	6,470,000	200,653	8,745,780	0	0	8,745,780	7,535,427
1975	17,072,661	8,745,780	7,535,427	7,500,000	6,470,000	221,897	11,626,544	0	0	11,626,544	10,017,513
1976	11,313,561	11,626,544	10,017,513	7,500,000	6,470,000	221,923	8,748,183	0	0	8,748,183	7,537,497
1977	5,551,188	8,748,183	7,537,497	7,500,000	6,470,000	100,584	228,786	0	0	228,786	197,124
1978	15,335,909	228,786	197,124	7,500,000	6,470,000	24,172	1,570,522	0	0	1,570,522	1,353,173
1979	17,825,429	1,570,522	1,353,173	7,500,000	6,470,000	78,663	5,347,288	0	0	5,347,288	4,607,262
1980	17,927,076	5,347,288	4,607,262	7,500,000	6,470,000	159,300	9,145,065	0	0	9,145,065	7,879,453
1981	9,015,200	9,145,065	7,879,453	7,500,000	6,470,000	145,434	4,044,830	0	0	4,044,830	3,485,055
1982	17,489,400	4,044,830	3,485,055	7,500,000	6,470,000	127,250	7,436,980	0	0	7,436,980	6,407,755
1983	24,361,989	7,436,980	6,407,755	7,500,000	6,470,000	271,108	17,557,861	0	0	17,557,861	15,127,979
1984	25,359,376	17,557,861	15,127,979	7,500,000	6,470,000	494,834	28,452,403	0	0	28,452,403	24,514,794
1985	21,246,109	28,452,403	24,514,794	7,500,000	6,470,000	668,102	35,060,409	1,226,819	0	33,833,590	29,151,263
1986	23,013,446	33,833,590	29,151,263	7,500,000	6,470,000	725,390	42,151,647	8,318,057	0	33,833,590	29,151,263
1987	15,640,478	33,833,590	29,151,263	7,500,000	6,470,000	725,390	34,778,679	945,089	0	33,833,590	29,151,263
1988	11,456,357	33,833,590	29,151,263	7,500,000	6,470,000	691,271	30,628,676	0	0	30,628,676	26,389,886
1989	9,921,847	30,628,676	26,389,886	7,500,000	6,470,000	607,588	25,972,935	0	0	25,972,935	22,378,466
1990	9,639,803	25,972,935	22,378,466	7,500,000	6,470,000	506,532	21,136,206	0	0	21,136,206	18,211,106
1991	12,170,021	21,136,206	18,211,106	7,500,000	6,470,000	431,288	18,904,938	0	0	18,904,938	16,288,630
1992	10,895,580	18,904,938	16,288,630	7,500,000	6,470,000	370,856	15,459,662	0	0	15,459,662	13,320,155
1993	18,160,118	15,459,662	13,320,155	7,500,000	6,470,000	374,796	19,274,984	0	0	19,274,984	16,607,464
1994	11,125,503	19,274,984	16,607,464	7,500,000	6,470,000	381,074	16,049,413	0	0	16,049,413	13,828,289
1995	20,047,166	16,049,413	13,828,289	7,500,000	6,470,000	407,098	21,719,481	0	0	21,719,481	18,713,660
1996	14,502,293	21,719,481	18,713,660	7,500,000	6,470,000	468,143	21,783,631	0	0	21,783,631	18,768,932
1997	21,622,438	21,783,631	18,768,932	7,500,000	6,470,000	544,496	28,891,573	0	0	28,891,573	24,893,185
1998	16,798,378	28,891,573	24,893,185	7,500,000	6,470,000	643,427	31,076,524	0	0	31,076,524	26,775,755
1999	15,934,210	31,076,524	26,775,755	7,500,000	6,470,000	680,355	32,360,379	0	0	32,360,379	27,881,934
2000	10,646,526	32,360,379	27,881,934	7,500,000	6,470,000	651,703	28,385,202	0	0	28,385,202	24,456,893
Total									0		
Averages:											
1953-1977	13,088,628			7,500,000	6,470,000	214,611		0	0	9,295,958	8,009,464
1931-1977	13,594,590			7,500,000	6,470,000	338,021		0	0	15,283,419	13,168,303
1906-2000	15,284,742			7,500,000	6,470,000	463,436		908,658	0	21,501,781	18,526,088

Variables

Storage	35,233,298 af
Sedimentation Rate (Active)	37,000 af/yr
Bank Storage	4%
Adjusted Storage (2060)	33,833,590 af
UB Demand Level	6,470,000 af/yr
LB Delivery	7,500,000 af/yr

Results

Average CRSP Evap	463,436 af/yr
Total Yield w/ CRSP evap	6,933,436 af/yr

Shortage Years	**Shortage**
1963	0 af
1964	0 af
1967	0 af
1968	0 af
1977	0 af

NM allocation (w/o evap) 722,250 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,684,611 af/yr
1931-1977	6,808,021 af/yr
1906-2000	6,933,436 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	0.00%
1931-1977	0.00%
1906-2000	0.00%

Upper Basin Yield Mass Balance Analysis

Run 8 - Use CRSP Minimum Power Pools, 7.50 maf Lower Basin Delivery, 6% Overall Shortage

CY	CR Natural Flow at Lee Ferry (plus)	Total Carry-Over Storage (plus)	CRSP Carry-Over Storage	Lower Basin Delivery (minus)	Upper Basin Use (minus)	Shared CRSP Evap (minus)	Net Available to Store (subtotal)	Spill to LC (minus)	Shortage (plus)	UC Basin Year-end Storage (equals)	CRSP Year-end Storage
1906	18,550,021	33,833,590	29,151,263	7,500,000	6,760,000	725,390	37,398,221	3,564,631	0	33,833,590	29,151,263
1907	21,201,694	33,833,590	29,151,263	7,500,000	6,760,000	725,390	40,049,894	6,216,304	0	33,833,590	29,151,263
1908	12,218,817	33,833,590	29,151,263	7,500,000	6,760,000	696,247	31,096,160	0	0	31,096,160	26,792,673
1909	22,356,301	31,096,160	26,792,673	7,500,000	6,760,000	696,247	38,496,213	4,662,623	0	33,833,590	29,151,263
1910	14,650,616	33,833,590	29,151,263	7,500,000	6,760,000	721,863	33,502,343	0	0	33,502,343	28,865,858
1911	15,499,729	33,502,343	28,865,858	7,500,000	6,760,000	721,863	34,020,209	186,619	0	33,833,590	29,151,263
1912	18,623,410	33,833,590	29,151,263	7,500,000	6,760,000	725,390	37,471,610	3,638,020	0	33,833,590	29,151,263
1913	14,536,373	33,833,590	29,151,263	7,500,000	6,760,000	720,660	33,389,303	0	0	33,389,303	28,768,462
1914	21,354,814	33,389,303	28,768,462	7,500,000	6,760,000	720,660	39,763,457	5,929,867	0	33,833,590	29,151,263
1915	13,623,277	33,833,590	29,151,263	7,500,000	6,760,000	711,041	32,485,825	0	0	32,485,825	27,990,019
1916	20,142,892	32,485,825	27,990,019	7,500,000	6,760,000	711,041	37,657,676	3,824,086	0	33,833,590	29,151,263
1917	22,942,804	33,833,590	29,151,263	7,500,000	6,760,000	725,390	41,791,004	7,957,414	0	33,833,590	29,151,263
1918	15,865,939	33,833,590	29,151,263	7,500,000	6,760,000	725,390	34,714,139	880,549	0	33,833,590	29,151,263
1919	12,651,369	33,833,590	29,151,263	7,500,000	6,760,000	700,804	31,524,155	0	0	31,524,155	27,161,438
1920	22,287,632	31,524,155	27,161,438	7,500,000	6,760,000	700,804	38,850,983	5,017,394	0	33,833,590	29,151,263
1921	22,526,781	33,833,590	29,151,263	7,500,000	6,760,000	725,390	41,374,981	7,541,391	0	33,833,590	29,151,263
1922	18,447,198	33,833,590	29,151,263	7,500,000	6,760,000	725,390	37,295,398	3,461,808	0	33,833,590	29,151,263
1923	19,024,046	33,833,590	29,151,263	7,500,000	6,760,000	725,390	37,872,246	4,038,656	0	33,833,590	29,151,263
1924	13,877,798	33,833,590	29,151,263	7,500,000	6,760,000	713,723	32,737,665	0	0	32,737,665	28,207,007
1925	14,430,701	32,737,665	28,207,007	7,500,000	6,760,000	696,458	32,211,908	0	0	32,211,908	27,754,010
1926	15,213,731	32,211,908	27,754,010	7,500,000	6,760,000	693,630	32,472,009	0	0	32,472,009	27,978,115
1927	19,539,212	32,472,009	27,978,115	7,500,000	6,760,000	710,894	37,040,326	3,206,736	0	33,833,590	29,151,263
1928	16,954,334	33,833,590	29,151,263	7,500,000	6,760,000	725,390	35,802,534	1,968,944	0	33,833,590	29,151,263
1929	21,829,585	33,833,590	29,151,263	7,500,000	6,760,000	725,390	40,677,785	6,844,195	0	33,833,590	29,151,263
1930	14,621,041	33,833,590	29,151,263	7,500,000	6,760,000	721,552	33,473,079	0	0	33,473,079	28,840,644
1931	8,474,134	33,473,079	28,840,644	7,500,000	6,760,000	649,207	27,038,006	0	0	27,038,006	23,296,139
1932	17,422,187	27,038,006	23,296,139	7,500,000	6,760,000	607,893	29,592,300	0	0	29,592,300	25,496,937
1933	12,183,500	29,592,300	25,496,937	7,500,000	6,760,000	606,523	26,909,278	0	0	26,909,278	23,185,226
1934	6,178,192	26,909,278	23,185,226	7,500,000	6,760,000	486,740	18,340,729	0	0	18,340,729	15,802,503
1935	12,630,349	18,340,729	15,802,503	7,500,000	6,760,000	374,189	16,336,890	0	0	16,336,890	14,075,981
1936	14,648,873	16,336,890	14,075,981	7,500,000	6,760,000	353,236	16,372,527	0	0	16,372,527	14,106,686
1937	14,306,056	16,372,527	14,106,686	7,500,000	6,760,000	350,375	16,068,208	0	0	16,068,208	13,844,483
1938	18,148,319	16,068,208	13,844,483	7,500,000	6,760,000	384,437	19,572,090	0	0	19,572,090	16,863,452
1939	11,164,059	19,572,090	16,863,452	7,500,000	6,760,000	384,685	16,091,464	0	0	16,091,464	13,864,520
1940	9,931,657	16,091,464	13,864,520	7,500,000	6,760,000	298,375	11,464,746	0	0	11,464,746	9,878,107
1941	20,116,678	11,464,746	9,878,107	7,500,000	6,760,000	308,188	17,013,235	0	0	17,013,235	14,658,725
1942	17,225,136	17,013,235	14,658,725	7,500,000	6,760,000	394,622	19,583,749	0	0	19,583,749	16,873,498
1943	13,731,401	19,583,749	16,873,498	7,500,000	6,760,000	411,974	18,643,176	0	0	18,643,176	16,063,094
1944	15,369,422	18,643,176	16,063,094	7,500,000	6,760,000	409,413	19,343,185	0	0	19,343,185	16,666,227
1945	14,140,528	19,343,185	16,666,227	7,500,000	6,760,000	411,216	18,812,498	0	0	18,812,498	16,208,983
1946	11,095,453	18,812,498	16,208,983	7,500,000	6,760,000	367,959	15,279,991	0	0	15,279,991	13,165,350
1947	16,439,486	15,279,991	13,165,350	7,500,000	6,760,000	349,831	17,109,646	0	0	17,109,646	14,741,793
1948	15,139,294	17,109,646	14,741,793	7,500,000	6,760,000	374,681	17,614,259	0	0	17,614,259	15,176,571
1949	16,933,584	17,614,259	15,176,571	7,500,000	6,760,000	404,213	19,883,630	0	0	19,883,630	17,131,878
1950	13,140,416	19,883,630	17,131,878	7,500,000	6,760,000	412,066	18,351,980	0	0	18,351,980	15,812,197
1951	12,505,894	18,351,980	15,812,197	7,500,000	6,760,000	373,115	16,224,759	0	0	16,224,759	13,979,368
1952	20,805,422	16,224,759	13,979,368	7,500,000	6,760,000	415,724	22,354,457	0	0	22,354,457	19,260,760
1953	11,165,419	22,354,457	19,260,760	7,500,000	6,760,000	443,316	18,816,559	0	0	18,816,559	16,212,482
1954	8,496,102	18,816,559	16,212,482	7,500,000	6,760,000	340,664	12,711,997	0	0	12,711,997	10,952,748
1955	9,413,908	12,711,997	10,952,748	7,500,000	6,760,000	221,725	7,644,180	0	0	7,644,180	6,586,280
1956	11,426,874	7,644,180	6,586,280	7,500,000	6,760,000	136,164	4,674,890	0	0	4,674,890	4,027,919
1957	21,500,963	4,674,890	4,027,919	7,500,000	6,760,000	179,726	11,736,128	0	0	11,736,128	10,111,931
1958	15,862,511	11,736,128	10,111,931	7,500,000	6,760,000	269,094	13,069,545	0	0	13,069,545	11,260,813
1959	9,598,169	13,069,545	11,260,813	7,500,000	6,760,000	231,199	8,176,515	0	0	8,176,515	7,044,944
1960	11,524,160	8,176,515	7,044,944	7,500,000	6,760,000	148,403	5,292,272	0	0	5,292,272	4,559,859
1961	10,010,259	5,292,272	4,559,859	7,500,000	6,760,000	71,693	970,838	0	0	970,838	836,481
1962	17,377,609	970,838	836,481	7,500,000	6,760,000	58,257	4,030,190	0	0	4,030,190	3,472,440
1963	8,840,900	4,030,190	3,472,440	7,500,000	6,760,000	47,922	-1,436,832	0	1,436,832	0	0
1964	10,863,586	0	0	7,500,000	6,760,000	5,017	-3,401,431	0	3,401,431	0	0
1965	19,875,027	0	0	7,500,000	6,760,000	64,111	5,550,916	0	0	5,550,916	4,782,709
1966	10,679,844	5,550,916	4,782,709	7,500,000	6,760,000	84,195	1,886,565	0	0	1,886,565	1,625,478
1967	11,670,830	1,886,565	1,625,478	7,500,000	6,760,000	25,101	-727,706	0	727,706	0	0
1968	13,739,932	0	0	7,500,000	6,760,000	5,017	-525,085	0	525,085	0	0
1969	15,272,159	0	0	7,500,000	6,760,000	15,626	996,533	0	0	996,533	858,620
1970	15,344,136	996,533	858,620	7,500,000	6,760,000	37,378	2,043,291	0	0	2,043,291	1,760,514
1971	15,493,659	2,043,291	1,760,514	7,500,000	6,760,000	61,006	3,215,943	0	0	3,215,943	2,770,880
1972	13,186,637	3,215,943	2,770,880	7,500,000	6,760,000	61,409	2,081,171	0	0	2,081,171	1,793,152
1973	18,650,193	2,081,171	1,793,152	7,500,000	6,760,000	95,054	6,376,310	0	0	6,376,310	5,493,874
1974	13,285,426	6,376,310	5,493,874	7,500,000	6,760,000	129,030	5,272,706	0	0	5,272,706	4,543,001
1975	17,072,661	5,272,706	4,543,001	7,500,000	6,760,000	145,674	7,939,693	0	0	7,939,693	6,840,897
1976	11,313,561	7,939,693	6,840,897	7,500,000	6,760,000	141,196	4,852,059	0	0	4,852,059	4,180,569
1977	5,551,188	4,852,059	4,180,569	7,500,000	6,760,000	56,671	-3,913,425	0	3,913,425	0	0
1978	15,335,909	0	0	7,500,000	6,760,000	16,297	1,059,611	0	0	1,059,611	912,969
1979	17,825,429	1,059,611	912,969	7,500,000	6,760,000	64,844	4,560,195	0	0	4,560,195	3,929,097
1980	17,927,076	4,560,195	3,929,097	7,500,000	6,760,000	139,663	8,087,608	0	0	8,087,608	6,968,341
1981	9,015,200	8,087,608	6,968,341	7,500,000	6,760,000	120,102	2,722,707	0	0	2,722,707	2,345,903
1982	17,489,400	2,722,707	2,345,903	7,500,000	6,760,000	96,342	5,855,764	0	0	5,855,764	5,045,368
1983	24,361,989	5,855,764	5,045,368	7,500,000	6,760,000	234,741	15,723,013	0	0	15,723,013	13,547,060
1984	25,359,376	15,723,013	13,547,060	7,500,000	6,760,000	453,124	26,369,265	0	0	26,369,265	22,719,947
1985	21,246,109	26,369,265	22,719,947	7,500,000	6,760,000	634,084	32,721,289	0	0	32,721,289	28,192,897
1986	23,013,446	32,721,289	28,192,897	7,500,000	6,760,000	713,548	40,761,187	6,927,597	0	33,833,590	29,151,263
1987	15,640,478	33,833,590	29,151,263	7,500,000	6,760,000	725,390	34,488,679	655,089	0	33,833,590	29,151,263
1988	11,456,357	33,833,590	29,151,263	7,500,000	6,760,000	688,216	30,341,731	0	0	30,341,731	26,142,652
1989	9,921,847	30,341,731	26,142,652	7,500,000	6,760,000	598,488	25,405,090	0	0	25,405,090	21,889,207
1990	9,639,803	25,405,090	21,889,207	7,500,000	6,760,000	491,515	20,293,378	0	0	20,293,378	17,484,920
1991	12,170,021	20,293,378	17,484,920	7,500,000	6,760,000	410,477	17,792,922	0	0	17,792,922	15,330,509
1992	10,895,580	17,792,922	15,330,509	7,500,000	6,760,000	344,374	14,084,127	0	0	14,084,127	12,134,985
1993	18,160,118	14,084,127	12,134,985	7,500,000	6,760,000	342,762	17,641,483	0	0	17,641,483	15,200,028
1994	11,125,503	17,641,483	15,200,028	7,500,000	6,760,000	343,606	14,163,380	0	0	14,163,380	12,203,269
1995	20,047,166	14,163,380	12,203,269	7,500,000	6,760,000	364,309	19,586,237	0	0	19,586,237	16,875,642
1996	14,502,293	19,586,237	16,875,642	7,500,000	6,760,000	420,147	19,408,383	0	0	19,408,383	16,722,402
1997	21,622,438	19,408,383	16,722,402	7,500,000	6,760,000	491,401	26,279,420	0	0	26,279,420	22,642,536
1998	16,798,378	26,279,420	22,642,536	7,500,000	6,760,000	585,341	28,232,457	0	0	28,232,457	24,325,287
1999	15,934,210	28,232,457	24,325,287	7,500,000	6,760,000	617,383	29,289,284	0	0	29,289,284	25,235,857
2000	10,646,526	29,289,284	25,235,857	7,500,000	6,760,000	583,949	25,091,861	0	0	25,091,861	21,619,327
Total									10,004,478		
Averages:											
1953-1977	13,088,628			7,500,000	6,760,000	122,986		0	400,179	5,093,532	4,388,624
1931-1977	13,594,590			7,500,000	6,760,000	259,645		0	212,861	11,602,960	9,997,193
1906-2000	15,284,742			7,500,000	6,760,000	416,577		805,494	105,310	19,283,636	16,614,918

Variables

Storage	35,233,298 af
Sedimentation Rate (Active)	37,000 af/yr
Bank Storage	4%
Adjusted Storage (2060)	33,833,590 af
UB Demand Level	6,760,000 af/yr
LB Delivery	7,500,000 af/yr

Results

Average CRSP Evap	416,577 af/yr
Total Yield w/ CRSP evap	7,176,577 af/yr

Shortage Years	**Shortage**
1963	1,436,832 af
1964	3,401,431 af
1967	727,706 af
1968	525,085 af
1977	3,913,425 af

NM allocation (w/o evap) 754,875 af/yr

Note: NM allocation is exclusive of its portion of CRSP evaporation. Navajo evaporation would be primarily charged against NM's allocation. Shared CRSP evaporation is already removed from UC demands.

Total Upper Basin depletion, inc. CRSP evap:

1953-1977	6,882,986 af/yr
1931-1977	7,019,645 af/yr
1906-2000	7,176,577 af/yr

Flow Adjustments:

1971	203,226 af
1972	226,985 af
1973	252,377 af
1974	196,384 af
1975	246,665 af
1976	173,250 af
1977	112,291 af
1978	152,187 af
1979	153,559 af
1980	161,893 af

Percentage shortage =

1953-1977	5.92%
1931-1977	3.15%
1906-2000	1.56%

APPENDIX B - Reservoir Storage

Upper Colorado River Basin Reservoir Storage

Upper Colorado River Basin Reservoirs	Complete	Live Capacity	CRSP Live	CRSP Active	CRSP Active +Other	State	Major Basin	Hydromet	Source
1 Big Sandy	X	38,300			38,300	WY	GR	BGRW	Hydromet
2 Blue Mesa	X	829,500	829,500	748,500	748,500	CO	CR	BMDC	Hydromet
3 Boulder Lake	X	22,280			22,280	WY	GR		Jade Henderson Superintendent for Region IV
4 Bottle Hollow		11,779			11,779	UT	GR	BHRU	
5 Crawford	X	13,970			13,970	CO	CR	CFRC	Erik Knight from GJ office
6 Crystal	X	17,536	17,536	13,000	13,000	CO	CR	CRRC	Hydromet
7 Currant Creek	X	15,460			15,460	UT	GR	CURU	Hydromet
8 Dillon	X	252,678			252,678	CO	CR		NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html NRCS Website
9 Eden		13,164			13,164	WY	GR	EDRU	
10 Electric Lake - Utah Power ar	X	31,500			31,500	UT	GR		Connely Baldwin at Pacific Corp. Connely.Baldwin@pacificorp.com or 801-220-4636
11 Elkhead	X	10,400			10,400	CO	GR		Bill Earley with the City of Craig Public Works Dept. 970-826-2014
12 Flaming Gorge	X	3,749,000	3,749,000	3,515,700	3,515,700	UT	GR	FGRU	Hydromet
13 Fontenelle	X	344,800			344,800	WY	GR	FTRW	Hydromet
14 Fremont Lake	X	30,899			30,899	WY	GR		Jade Henderson Superintendent for Region IV
15 Gould	X	10,380			10,380	CO	CR		George Wear with Colorado Division of Water Resources george.wear@dwr.state.co.us
16 Fruitgrowers	X	4,460			4,460	CO	CR	FGRC	Hydromet
17 Granby	X	540,033			540,033	CO	CR		NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html
18 Green Mountain	X	153,678			153,678	CO	CR	GMRC	NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html
19 Groundhog	X	27,500			27,500	CO	CR		NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html
20 Gurley	X	12,035			12,035	CO	CR		George Wear with Colorado Division of Water Resources george.wear@dwr.state.co.us
21 Homestake	X	42,882			42,882	CO	CR		NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html
22 Jackson Gulch	X	9,951			9,951	CO	CR	JGRC	Hydromet
23 Joe's Valley	X	61,590			61,590	UT	GR	JVRU	Hydromet
24 Johnson		15,300			15,300	CO	CR		
25 Kenny Reservoir (Taylor Drav	X	9,400			9,400	CO	CR		Erin.Light@state.co.us Division 6 Water Resources for State of Colorado
26 Lake Powell	X	24,322,000	24,322,000	20,309,919	20,309,919	AZ	CR	GLDA	Hydromet
27 Lake Viva Naughton	X	69,645			69,645	WY	GR		Connely Baldwin at Pacific Corp. Connely.Baldwin@pacificorp.com or 801-220-4636
28 Lemon	X	39,792			39,792	CO	SJR	LMRC	Hydromet
29 Long Park		14,600			14,600	UT	GR		
30 McPhee	X	247,400			247,400	CO	CR	MCRC	Hydromet
31 Meeks Cabin	X	29,870			29,870	WY	GR	MERW	Hydromet
32 Millsite		20,000			20,000	UT	GR		
33 Miramonte	X	11,620			11,620	CO	CR		George Wear with Colorado Division of Water Resources george.wear@dwr.state.co.us
34 Moon Lake	X	49,500			49,500	UT	GR	MNLU	Hydromet
35 Morgan Lake Dam		42,800			42,800	NM	SJR		
36 Morrow Point	X	117,025	117,025	42,120	42,120	CO	CR	MPRC	Hydromet
37 Narraguinnep	X	22,700			22,700	CO	SJR		NRCS Website http://www.wcc.nrcs.usda.gov/wsf/reservoir/resv_rpt.html
38 Navajo	X	1,696,000	1,696,000	1,036,100	1,036,100	NM	SJR	NVRN	Hydromet
39 New Fork Lake	X	20,340			20,340	WY	GR		Jade Henderson Superintendent for Region IV
40 Paonia	X	16,703			16,703	CO	CR	PARC	Hydromet
41 Pelican Lake		15,850			15,850	UT	GR		
42 Pleasant Valley (Lake Catam	X	7,275			7,275	CO	CR		Erin.Light@state.co.us Division 6 Water Resources for State of Colorado
43 Recapture Creek		16,000			16,000	UT	GR		
44 Redfleet	X	25,700			25,700	UT	GR	RFRU	Hydromet
45 Ridgway	X	82,980			82,980	CO	CR	RWRC	Hydromet
46 Rifle Gap	X	12,708			12,708	CO	CR	RGRC	Hydromet
47 Ruedi	X	102,330			102,330	CO	CR	RURC	Great Planes Region Website
48 Scofield	X	65,800			65,800	UT	GR	SFRU	Hydromet
49 Shadow Mountain	X	18,368			18,368	CO	CR	SMRC	Great Planes Region Website
50 Silver Jack	X	13,000			13,000	CO	CR	SJRC	Hydromet
51 Soldier Creek	X	1,105,910			1,105,910	UT	GR	SCRU	Hydromet
52 Stagecoach	X	33,275			33,275	CO	GR		Erin.Light@state.co.us Division 6 Water Resources for State of Colorado
53 Starvation	X	165,320			165,320	UT	GR	SVRU	Hydromet
54 Stateline	X	13,880			13,880	WY	GR	SLRW	Hydromet
55 Steamboat Lake	X	25,400			25,400	CO	GR		Erin.Light@state.co.us Division 6 Water Resources for State of Colorado
56 Steinaker	X	34,455			34,455	UT	GR	STRU	Hydromet
57 Taylor Park	X	106,210			106,210	CO	CR	TPRC	Hydromet
58 Upper Stillwater	X	31,382			31,382	UT	GR	USRU	Hydromet
59 Vallecito	X	125,400			125,400	CO	SJR	VCRC	Hydromet
60 Vega	X	33,311			33,311	CO	CR	VGRU	Erik Knight from GJ office
61 Williams Creek	X	10,084			10,084	CO	CR		George Wear with Colorado Division of Water Resources george.wear@dwr.state.co.us
62 Williams Fork	X	96,824			96,824	CO	CR	WFRC	Great Planes Region Website
63 Willow Lake	X	18,816			18,816	WY	GR		Jade Henderson Superintendent for Region IV
64 Willow Creek	X	10,550			10,550	CO	CR	WCRC	Great Planes Region Website
65 Wolford Mountain	X	66,000			66,000	CO	CR		George Wear with Colorado Division of Water Resources george.wear@dwr.state.co.us
66 Yamcolo	X	8,000			8,000	CO	GR		Erin.Light@state.co.us Division 6 Water Resources for State of Colorado
	Total Capacity	35,233,298	30,731,061	25,665,339	30,167,576				

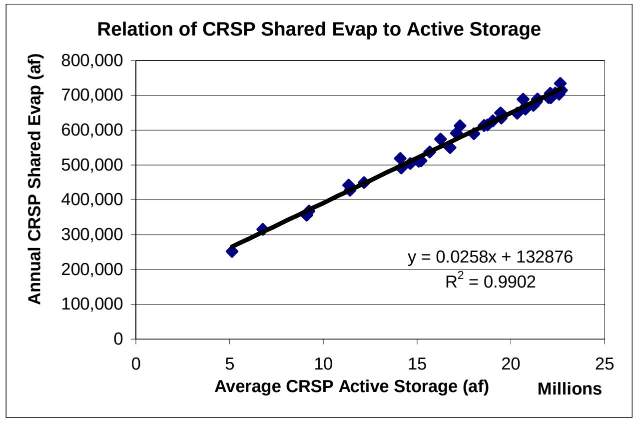
APPENDIX C - CRSP Evaporation Analysis

Relationships of CRSP Shared Reservoir Evaporation to Total CRSP Storage

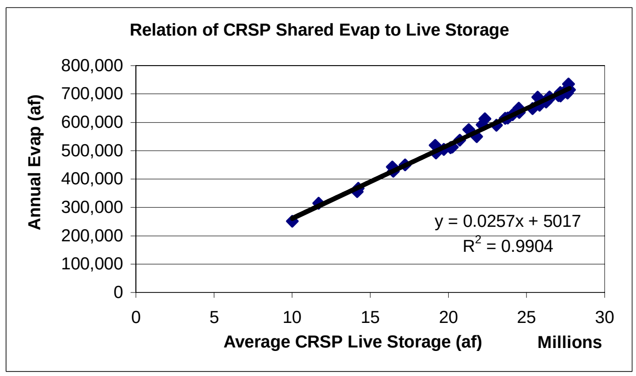
Year	Average CRSP Live Storage (af)	Average CRSP Active Storage (af)	CRSP Shared Evap (af)
1968	10,006,534	5,123,250	251,646
1969	11,701,142	6,764,000	315,083
1970	14,222,401	9,231,741	367,164
1971	16,417,858	11,354,088	442,260
1972	17,229,715	12,165,945	449,544
1973	19,703,066	14,639,296	504,409
1974	22,158,563	17,094,793	590,940
1975	23,634,096	18,570,326	613,612
1976	24,105,743	19,041,973	626,694
1977	20,730,592	15,672,536	537,406
1978	19,158,480	14,106,380	519,065
1979	22,336,514	17,284,414	612,639
1980	25,709,770	20,657,670	688,502
1981	25,392,305	20,340,205	648,525
1982	25,835,729	20,783,629	666,691
1983	27,692,454	22,640,354	734,416
1984	27,759,568	22,707,468	714,727
1985	27,619,938	22,567,838	702,973
1986	27,414,909	22,362,809	706,131
1987	27,153,464	22,101,364	705,172
1988	26,465,639	21,413,539	689,455
1989	24,540,351	19,488,251	634,821
1990	21,806,134	16,754,034	549,702
1991	20,141,572	15,089,472	510,689
1992	19,208,740	14,156,640	491,352
1993	21,297,564	16,245,464	573,884
1994	23,080,796	18,028,696	589,440
1995	24,500,724	19,448,624	649,206
1996	26,252,053	21,199,953	671,123
1997	26,416,641	21,364,541	681,115
1998	27,174,302	22,122,202	693,294
1999	27,050,819	21,998,719	694,007
2000	25,830,330	20,778,230	660,675
2001	23,802,258	18,750,158	614,593
2002	20,256,954	15,204,854	512,030
2003	16,472,537	11,420,437	427,526
2004	14,160,551	9,108,451	355,545

Regression Analyses

Active Storage:



Live Storage:



Notes:

(1) Historic calendar year data from Bureau of Reclamation. Average storage values are based on the average of the end-of-year storage amounts for the year indicated and for the previous year. Storage amounts include storage in all CRSP units, including Lake Powell, Flaming Gorge Reservoir, Navajo Reservoir and the Aspinall Unit (Blue Mesa, Morrow Point and Crystal reservoirs).

(2) CRSP shared evaporation includes lake evaporation for Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit reservoirs, and is shared between the Upper Division States in proportions to their Upper Colorado River Basin Compact Article III(a) apportionments. CRSP shared evaporation is approximately 10,000 af at zero live CRSP storage (5,000 af based on the regression analyses) and approximately 130,000 af if storage in all CRSP reservoirs were at the top of the inactive pools (133,000 af based on the regression analysis). Lake evaporation for Navajo Reservoir is not included in CRSP shared evaporation.

(3) Data for the period 1968-2004 were used in the regression analyses. Data prior to 1968 do not reflect a normal distribution of storage between CRSP unit reservoirs under future operational conditions (for example, Navajo Reservoir storage remained below the top of the inactive pool required for operation of the Navajo Indian Irrigation Project diversion from 1962 when it began storing water until 1968, and Morrow Point Reservoir began operation in 1968). For the period 1968-1977, the historic average end-of-year CRSP storage and annual CRSP evaporation amount were increased to reflect the average storage of 15,670 af and average evaporation amount of 340 af occurring at Crystal Reservoir after its initial filling in 1978.

Historic Storage and Evaporation at Colorado River Storage Project Reservoirs

	Lake Powell		Flaming Gorge Reservoir		Navajo Reservoir		Blue Mesa Reservoir		Morrow Point Reservoir		Crystal Reservoir		Total All CRSP Reservoirs			
Year	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	Annual Evap Amount (af)	EOY Live Storage (af)	EOY Active Storage (af)	Total Annual Evap (af)	Annual Shared Evap (af)
1961	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1962	0	0	13,000	200	57,000	700	0	0	0	0	0	0	70,000	0	900	200
1963	970,000	25,000	883,500	20,000	331,834	8,323	0	0	0	0	0	0	2,185,334	650,500	53,323	45,000
1964	4,226,877	76,171	1,097,900	42,320	382,320	10,647	0	0	0	0	0	0	5,707,097	1,199,800	129,137	118,490
1965	6,755,838	144,900	2,395,300	47,402	404,111	14,630	0	100	0	0	0	0	9,555,248	5,026,100	207,031	192,401
1966	5,892,764	181,801	2,243,300	65,869	400,389	10,730	248,900	2,500	0	0	0	0	8,785,352	4,178,900	260,900	250,170
1967	6,237,331	158,145	2,288,300	66,614	588,132	13,048	321,500	4,500	0	0	0	0	9,435,263	4,641,100	242,308	229,259
1968	7,039,300	185,829	1,912,939	59,077	973,592	18,631	511,900	6,000	108,735	400	0	0	10,546,465	5,605,400	269,937	251,306
1969	9,527,661	252,105	1,565,599	54,074	1,043,002	22,326	652,343	8,064	35,875	500	0	0	12,824,480	7,922,600	337,068	314,743
1970	12,014,346	305,979	1,761,250	51,442	1,049,190	22,564	647,667	8,804	116,528	600	0	0	15,588,982	10,540,882	389,389	366,824
1971	12,973,499	365,252	2,704,322	68,523	991,296	20,505	431,077	7,297	115,200	848	0	0	17,215,394	12,167,294	462,425	441,920
1972	12,611,547	362,114	3,086,584	79,091	982,869	19,991	415,961	7,155	115,736	845	0	0	17,212,697	12,164,597	469,195	449,204
1973	17,397,040	417,269	2,938,138	77,932	1,112,631	28,408	598,694	8,028	115,592	839	0	0	22,162,095	17,113,995	532,477	504,069
1974	17,298,382	498,708	3,262,393	83,468	970,485	21,646	476,431	7,586	116,000	837	0	0	22,123,690	17,075,590	612,246	590,600
1975	19,846,968	521,418	3,430,797	83,664	1,185,693	26,432	533,575	7,360	116,128	831	0	0	25,113,161	20,065,061	639,704	613,272
1976	18,139,140	533,889	3,129,279	83,640	1,205,201	25,255	478,276	7,980	115,088	845	0	0	23,066,984	18,018,884	651,609	626,354
1977	15,050,697	467,624	1,990,703	62,883	979,918	22,439	235,328	5,729	113,928	832	7,714	100	18,378,288	13,326,188	559,605	537,166
1978	15,343,792	443,338	2,673,304	66,716	1,195,470	24,307	594,351	7,871	115,688	840	16,068	300	19,938,673	14,886,573	543,372	519,065
1979	20,395,402	536,289	2,397,144	67,120	1,233,240	27,623	579,788	8,040	111,536	840	17,244	349	24,734,354	19,682,254	640,261	612,639
1980	21,602,374	606,694	3,013,072	72,311	1,382,000	28,916	558,000	8,314	113,305	836	16,435	348	26,685,186	21,633,086	717,417	688,502
1981	19,610,804	566,573	2,783,198	74,001	1,234,201	26,237	340,276	6,763	114,242	839	16,703	349	24,099,424	19,047,324	674,762	648,525
1982	22,052,326	579,638	3,307,239	78,299	1,475,159	28,337	607,227	7,570	113,713	836	16,369	348	27,572,033	22,519,933	695,028	666,691
1983	22,095,450	638,987	3,451,988	85,654	1,545,720	30,691	593,402	8,583	113,018	842	13,297	350	27,812,875	22,760,775	765,108	734,416
1984	21,991,934	621,218	3,379,535	84,057	1,536,197	31,194	666,201	8,256	115,379	844	17,015	351	27,706,261	22,654,161	745,921	714,727
1985	22,324,682	613,050	3,116,556	80,358	1,392,531	31,206	567,471	8,373	115,476	842	16,900	350	27,533,616	22,481,516	734,179	702,973
1986	21,900,656	615,398	3,257,068	81,239	1,429,801	30,200	576,633	8,304	115,023	841	17,021	350	27,296,202	22,244,102	736,331	706,131
1987	22,041,008	613,810	3,216,414	81,897	1,075,143	24,350	547,283	8,279	113,913	839	16,965	349	27,010,726	21,958,626	729,523	705,172
1988	21,223,202	603,875	2,958,441	77,191	1,149,810	24,336	458,550	7,206	114,808	836	15,742	348	25,920,552	20,868,452	713,791	689,455
1989	18,292,024	551,911	2,943,401	73,516	1,230,357	26,906	563,467	8,217	114,531	832	16,369	346	23,160,150	18,108,050	661,727	634,821
1990	15,246,718	464,809	3,049,072	75,352	1,381,613	26,704	647,094	8,362	110,936	832	16,686	346	20,452,119	15,400,019	576,406	549,702
1991	14,251,955	420,198	3,328,132	80,305	1,551,852	30,621	571,167	9,008	111,922	831	15,997	346	19,831,025	14,778,925	541,310	510,689
1992	13,334,385	403,360	3,013,793	78,487	1,528,220	31,554	580,946	8,354	113,617	812	15,495	338	18,586,456	13,534,356	522,907	491,352
1993	18,402,436	483,699	3,317,500	80,461	1,567,023	30,954	594,902	8,546	112,000	832	14,811	346	24,008,671	18,956,571	604,838	573,884
1994	17,220,702	504,284	2,835,277	75,469	1,391,103	30,450	579,329	8,525	110,880	821	15,629	342	22,152,920	17,100,820	619,890	589,440
1995	21,392,360	560,150	3,285,793	79,319	1,461,480	30,153	586,169	8,569	109,120	825	13,607	343	26,848,529	21,796,429	679,359	649,206
1996	20,497,896	582,091	3,248,287	79,159	1,187,295	27,184	601,723	8,707	105,401	823	14,976	343	25,655,578	20,603,478	698,308	671,123
1997	21,595,054	592,707	3,323,228	78,851	1,558,033	28,612	578,393	8,392	108,842	823	14,154	342	27,177,704	22,125,604	709,727	681,115
1998	21,654,054	605,297	3,399,837	78,646	1,412,077	29,148	577,927	8,180	110,739	827	16,265	344	27,170,899	22,118,799	722,442	693,294
1999	21,443,640	605,738	3,269,090	78,352	1,500,893	27,969	589,147	8,749	112,771	825	15,198	343	26,930,739	21,878,639	721,976	694,007
2000	19,823,236	576,898	2,991,270	74,194	1,288,792	26,850	504,611	8,409	107,722	829	14,289	345	24,729,920	19,677,820	687,525	660,675
2001	17,995,952	532,968	2,876,393	72,363	1,334,015	26,563	544,265	8,102	109,410	819	14,561	341	22,874,596	17,822,496	641,156	614,593
2002	13,773,841	436,496	2,631,819	67,919	826,816	20,891	283,191	6,507	109,636	783	14,009	326	17,639,312	12,587,212	532,921	512,030
2003	11,486,774	352,779	2,606,058	67,223	710,076	17,085	376,564	6,359	111,708	823	14,582	343	15,305,762	10,253,662	444,611	427,526
2004	8,663,616	278,349	2,742,643	68,248	991,373	20,353	491,453	7,778	109,666	826	16,589	344	13,015,340	7,963,240	375,898	355,545

Notes:

(1) Lake Powell statistics: Dead storage 1,893,000 af at elevation 3370; Live storage capacity 24,322,000 af between elevations 3370 and 3700; Active storage capacity 20,325,000 af between elevations 3490 and 3700. Storage began March 1963.

(2) Flaming Gorge Reservoir statistics: Dead storage 39,700 af at elevation 5740; Live storage capacity 3,749,500 af between elevations 5740 and 6040; Active storage capacity 3,516,000 af between elevations 5871 and 6040. Storage began November 1962.

(3) Navajo Reservoir statistics: Dead storage 12,600 af at elevation 5775; Live storage capacity 1,701,300 af between elevations 5775 and 6085; Active storage capacity 1,039,500 af between elevations 5990 and 6085. Storage began June 1962.

(4) Aspinall Unit statistics:

Blue Mesa Reservoir - Dead storage 111,200 af at elevation 7358; Live storage capacity 829,600 af between elevations 7358 and 7519; Active storage capacity 748,800 af between elevations 7393 and 7519. Storage began October 1965. End-of-year 1965 total storage for Blue Mesa Reservoir was 85,240 af (0 live storage).

Morrow Point Reservoir - Dead storage 165 af at elevation 6808; Live storage capacity 117,000 af between elevations 6808 and 7160; Active storage capacity 42,000 af between elevations 7100 and 7160. Storage began January 1968.

Crystal Reservoir - Dead storage 8,000 af at elevation 6670; Live storage capacity 17,000 af between elevations 6670 and 6755; Active storage capacity 13,000 af between elevations 6700 and 6755. Storage began March 1977.

(5) Total CRSP Live storage capacity is 30,736,400 af, and total CRSP Active storage capacity is 25,684,300 af. The total CRSP inactive storage capacity is 5,052,100 af.

(6) Evaporation amounts were computed using the method and coefficients described in Historical Inflows, Colorado River Storage Project, Bureau of Reclamation (Tom Ryan), October 1993.

(7) The following evaporation amounts are estimated from calculated evaporation for other years and relative total storage amounts: Lake Powell for 1963, Flaming Gorge Reservoir for 1962-63, Navajo Reservoir for 1962, Blue Mesa Reservoir for 1966-68, Morrow Point Reservoir for 1968-70, and Crystal Reservoir for 1977-78. These evaporation amounts for Flaming Gorge, Navajo and Blue Mesa reservoirs also were reduced for when storage began. Crystal Reservoir evaporation for 1979-2004 was estimated based on the evaporation amounts at Morrow Point Reservoir and the ratio of the surface area of Crystal Reservoir to the surface area of Morrow Point Reservoir at full capacity.

(8) CRSP shared evaporation includes lake evaporation for Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit reservoirs, and is shared between the Upper Division States in proportion to their Upper Colorado River Basin Compact Article III(a) apportionments. Lake evaporation for Navajo Reservoir is accounted separately.

APPENDIX D - New Mexico Depletion Schedule

Preliminary May 2006

STATE OF NEW MEXICO SCHEDULE OF ANTICIPATED UPPER BASIN DEPLETIONS
(Units: 1000 acre-feet per year)

	2000	2010	2020	2030	2040	2050	2060
IRRIGATION USES (1)							
Navajo Nation Irrigation:							
Navajo Indian Irrigation Project	150.0	215.0	250.0	270.0	270.0	270.0	270.0
Fruitland-Cambridge Irrigation Project	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Hogback-Cudei Irrigation Project	15.5	15.5	21.3	21.3	21.3	21.3	21.3
Chaco River drainage irrigation	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Crystal area irrigation	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Navajo Nation Irrigation Subtotal	176.9	241.9	282.7	302.7	302.7	302.7	302.7
Non-Navajo Irrigation:							
Above Navajo Dam (including Jicarilla)	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Upper San Juan (excluding Hammond)	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Hammond Irrigation Project	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Animas River ditches	40.7	40.7	40.7	40.7	40.7	40.7	40.7
La Plata River ditches	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Farmers Mutual Ditch	11.2	11.2	11.2	11.2	11.2	11.2	11.2
Jewett Valley Ditch	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Chaco River drainage irrigation	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Non-Navajo Irrigation Subtotal	86.5	86.5	86.5	86.5	86.5	86.5	86.5
Irrigation Total	263.4	328.4	369.2	389.2	389.2	389.2	389.2
STOCKPOND EVAPORATION AND STOCK USE	4.0	4.0	4.0	4.0	4.0	4.0	4.0
MUNICIPAL AND DOMESTIC USES (1)							
Current Municipal and Industrial Uses	9.7	9.7	9.7	9.7	9.7	9.7	9.7
Animas-La Plata Project:							
San Juan Water Commission	1.0	5.0	10.4	10.4	10.4	10.4	10.4
Navajo Nation	0.0	1.0	2.0	2.3	2.3	2.3	2.3
La Plata Conservancy District	0.0	0.0	0.8	0.8	0.8	0.8	0.8
Ridges Basin Reservoir Evaporation - NM share	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Animas-La Plata Project Subtotal	1.0	6.0	13.3	13.6	13.6	13.6	13.6
Navajo-Gallup Water Supply Project: (2)							
Navajo Nation	0.0	0.0	7.9	10.2	12.5	12.5	12.5
Jicarilla Apache Nation	0.0	0.0	0.8	1.0	1.2	1.2	1.2
Navajo-Gallup Project Subtotal (within Basin)	0.0	0.0	8.7	11.2	13.7	13.7	13.7
Navajo Nation Municipal Use, Future (exc. NGWSP)	0.0	0.0	1.0	1.0	2.0	2.0	2.0
Jicarilla Apache Nation Municipal Use (exc. NGWSP)	0.0	0.0	0.0	0.4	0.6	0.6	0.6
Scattered Rural Domestic (including Jicarilla)	1.0	1.0	1.0	1.1	1.1	1.2	1.2
Municipal and Domestic Total	11.7	16.7	33.7	37.0	40.7	40.8	40.8
POWER AND INDUSTRIAL USES							
PNM - Navajo Reservoir contract (3)	16.2	16.2	16.2	16.2	16.2	16.2	16.2
BHP Billiton	37.0	37.0	38.0	39.0	39.0	39.0	39.0
Bloomfield Industrial	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Navajo Nation - Shiprock	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Navajo-Gallup Water Supply Project - NAPI (2)	0.0	0.0	0.7	0.7	0.7	0.7	0.7
Small Navajo Reservoir Contracts	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Power and Industrial Total	56.1	56.1	57.8	58.8	58.8	58.8	58.8
EXPORTS							
San Juan-Chama Project	105.2	105.2	105.2	105.2	105.2	105.2	105.2
Navajo-Gallup Water Supply Project: (2)							
Navajo Nation in New Mexico	0.0	0.0	4.0	5.8	7.6	7.6	7.6
City of Gallup	0.0	0.0	4.7	6.1	7.5	7.5	7.5
Navajo-Gallup Project Subtotal (Export)	0.0	0.0	8.7	11.9	15.1	15.1	15.1
Export Total	105.2	105.2	113.9	117.1	120.3	120.3	120.3
RESERVOIR EVAPORATION							
Navajo Reservoir Evaporation	28.3	28.0	27.7	27.7	27.7	27.7	27.7
Small Reservoir Evaporation	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Reservoir Evaporation Total	29.5	29.2	28.9	28.9	28.9	28.9	28.9
TOTAL DEPLETIONS (4)	469.9	539.6	607.5	635.0	641.9	642.0	642.0
State Share of Upper Basin Yield (5)	642.4	642.4	642.4	642.4	642.4	642.4	642.4
Remaining Available (5,6)	172.5	102.8	34.9	7.4	0.5	0.4	0.4
Percent of State Share Remaining	26.9%	16.0%	5.4%	1.2%	0.1%	0.1%	0.1%

NOTES:

(1) Does not reflect post-1965 transfers from irrigation to municipal and industrial uses.

(2) Proposed Navajo-Gallup Water Supply Project depletions in New Mexico total 29,500 acre-feet per year. Exports to Gallup are anticipated to be supplied through a subcontract with the Jicarilla Apache Nation. Exports for Navajo Nation uses in Arizona ar

(3) Supplied through a subcontract with the Jicarilla Apache Nation.

(4) This is a schedule of anticipated depletions for planning purposes only. It is not a tabulation or determination of water rights or actual uses. Total depletions exclude New Mexico's share of reservoir evaporation from the major reservoirs constructed

(5) This depletion schedule does not attempt to interpret the Colorado River Compact, the Upper Colorado River Basin Compact, or any other element of the "Law of the River." This schedule should not be construed as an acceptance of any assumption that lim

(6) Reserved.

APPENDIX E - Upper Colorado River Commission Resolution

RESOLUTION OF THE UPPER COLORADO RIVER COMMISSION

Regarding the Availability of Water from Navajo Reservoir for Navajo Nation Uses within the State of New Mexico

WHEREAS, the State of New Mexico has proposed the Navajo-Gallup Water Supply Project to provide a needed renewable water supply from the San Juan River for municipal and domestic uses for Indian and non-Indian communities located within New Mexico in both the Upper Basin and the Lower Basin; and

WHEREAS, the State of New Mexico and the Navajo Nation on April 19, 2005, executed the San Juan River Basin in New Mexico Navajo Nation Water Rights Settlement Agreement (the "Settlement Agreement"), which is conditioned upon, among other things, the implementation of the Navajo Nation components of the Navajo-Gallup Water Supply Project within New Mexico; and

WHEREAS, the source of water supply for the proposed Navajo-Gallup Water Supply Project would be Navajo Reservoir and the San Juan River in New Mexico; and

WHEREAS, water from Navajo Reservoir and the San Juan River would be delivered to the proposed Navajo-Gallup Water Supply Project to meet the water demands of Navajo Nation communities in New Mexico through a proposed Settlement Contract between the United States, acting through the Secretary of the Interior, and the Navajo Nation (Appendix 4 to the Settlement Agreement); and

WHEREAS, Public Law 87-483 at section 11(a) requires that no new long-term contracts "... shall be entered into for the delivery of water stored in Navajo Reservoir or any other waters of the San Juan River and its tributaries, as aforesaid, until the Secretary has determined by hydrologic investigations that sufficient water to fulfill said contract is reasonably likely to be available for use in the State of New Mexico during the term thereof under the allocations made in articles III and XIV of the Upper Colorado River Basin compact, and has submitted such determination to the Congress of the United States and the Congress has approved such contracts"; and

WHEREAS, pursuant to Public Law 87-483, and in furtherance of the Jicarilla Apache Tribe Water Rights Settlement Act of 1992 and the Navajo Reservoir water supply contract approved by said Act, the Secretary of the Interior on February 2, 1989, approved the report on "Hydrologic Determination, 1988, Water Availability from Navajo Reservoir and the Upper Colorado River Basin for Use in New Mexico" (the "1988 Hydrologic Determination"); and

WHEREAS, the 1988 Hydrologic Determination evaluated the availability of water from the Navajo Reservoir supply for uses in New Mexico through the 2040 planning horizon; and

WHEREAS, an update and extension to the 1988 Hydrologic Determination is needed to evaluate the availability of water from the Navajo Reservoir supply through a 2060 planning horizon under the allocation of water made to the State of New Mexico by the Upper Colorado River Basin Compact for the purpose of furthering Congressional legislative approval of the Settlement Agreement, the authorization of the proposed Navajo-Gallup Water Supply Project, and the legislative approval of the proposed Settlement Contract for the Navajo Nation's project uses in New Mexico; and

WHEREAS, the proposed Settlement Contract between the United States and the Navajo Nation would provide water supplies for Navajo Nation uses in New Mexico under both the Navajo-Gallup Water Supply Project and the Navajo Indian Irrigation Project which was authorized by Public Law 87-483, and would supersede the existing Navajo Reservoir water supply contract for the Navajo Indian Irrigation Project; and

WHEREAS, the US Bureau of Reclamation has presented to the Upper Colorado River Commission for its consideration a draft hydrologic determination, dated May 2006, that evaluates the availability of water from the Navajo Reservoir supply through 2060 and shows: (1) at least 5.76 million acre-feet of water is reasonably available annually for use by the Upper Basin, exclusive of reservoir evaporation at Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit reservoirs of the Colorado River Storage Project; and (2) sufficient water is reasonably likely to be available from the Navajo Reservoir supply to fulfill the proposed Settlement Contract for the Navajo Nation's uses in New Mexico under the Navajo-Gallup Water Supply Project and the Navajo Indian Irrigation Project, in addition to existing Navajo Reservoir water supply contracts for other uses, under the allocations made to New Mexico in Articles III and XIV of the Upper Colorado River Basin Compact; and

WHEREAS, the Settlement Agreement would provide at subparagraph 9.3.1: "The Navajo Nation and the United States agree that the State of New Mexico may administer in priority water rights in the San Juan River Basin in New Mexico, including rights of the Navajo Nation, as may be necessary for New Mexico to comply with its obligations under interstate compacts and other applicable law"; and

WHEREAS, the Upper Colorado River Commission supports water resource development in the Upper Colorado River Basin to enable the Upper Division States to fully develop their compact apportionments of Colorado River water while meeting compact obligations relating to the flow of the Colorado River at Lee Ferry; and

WHEREAS, it is the position of the Upper Colorado River Commission and the Upper Division States that, with the delivery at Lee Ferry of 75 million acre-feet of water in each period of ten consecutive years, the water supply available in the Colorado River

System below Lee Ferry is sufficient to meet the apportionments to the Lower Basin provided for in Articles III (a) and III (b) of the Colorado River Compact; and

WHEREAS, it is the position of the Upper Colorado River Commission and the Upper Division States that the obligation of the Upper Basin under Article III(c) of the Colorado River Compact to deliver water toward the Mexican Treaty obligation does not require the delivery at Lee Ferry of 0.75 million acre-feet of water annually; and

WHEREAS, the Upper Colorado River Commission anticipates that the Upper Division States will take all actions necessary to ensure that all Upper Basin States have access to their respective apportionments as specified in the Upper Colorado River Basin Compact; and

WHEREAS, the Upper Colorado River Commission on June 19, 2003, resolved that: (1) "the States of Colorado, New Mexico, Utah and Wyoming, support and to the extent necessary consent to the diversion of water from the Upper Basin for use in the Lower Basin solely within New Mexico via the proposed Navajo-Gallup Water Supply Project; provided, that any water so diverted by said project to the Lower Basin portion of New Mexico, being a depletion of water at Lee Ferry, shall be a part of the consumptive use apportionment made to the State of New Mexico by Article III (a) of the Upper Colorado River Compact;" and (2) "the Upper Colorado River Commission supports such Congressional action as may be necessary to authorize the Navajo-Gallup Water Supply Project."

NOW, THEREFORE, BE IT RESOLVED by the Upper Colorado River Commission, that the Commission supports Congressional action to: (1) approve the Settlement Agreement; (2) authorize the proposed Navajo-Gallup Water Supply Project; and (3) approve the proposed Settlement Contract for the Navajo Nation's uses in New Mexico from the Navajo Reservoir supply under the Navajo-Gallup Water Supply Project and the Navajo Indian Irrigation Project.

BE IT FURTHER RESOLVED, that while the Upper Colorado River Commission does not endorse all of the study assumptions used by the Bureau of Reclamation in its May 2006 draft hydrologic determination, including an assumption of a 6 percent allowable overall shortage, and specifically disagrees with the modeling assumption of a minimum Upper Basin delivery of 8.25 million acre-feet annually at Lee Ferry, the Commission supports a determination by the Secretary of the Interior that at least 5.76 million acre-feet of water is available annually for use by the Upper Basin, exclusive of reservoir evaporation at Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit reservoirs of the Colorado River Storage Project.

BE IT FURTHER RESOLVED, that the Upper Colorado River Commission supports a determination by the Secretary of the Interior that sufficient water is reasonably likely to be available to fulfill the proposed Settlement Contract for the Navajo Nation's uses in New Mexico from the Navajo Reservoir supply under the Navajo-Gallup Water Supply Project and the Navajo Indian Irrigation Project, in addition to existing Navajo Reservoir water supply contracts for other uses, under the allocations made to New Mexico in Articles III and XIV of the Upper Colorado River Basin Compact.

BE IT FURTHER RESOLVED, that nothing in this Resolution, or resulting from the adoption of this Resolution, shall limit the right or ability of any Upper Basin State to develop the full apportionment made to it under the Colorado River Compact and the Upper Colorado River Basin Compact.

BE IT FURTHER RESOLVED, that a copy of this resolution be transmitted to the Regional Director, Upper Colorado Region, Bureau of Reclamation, Salt Lake City, Utah.

CERTIFICATE

I, Don A. Ostler, Executive Director and Secretary of the Upper Colorado River Commission, do hereby certify that the Upper Colorado River Commission adopted the above Resolution at its regular meeting held in Jackson Hole, Wyoming, on June 5, 2006.

WITNESS my hand this 9th day of June 2006.

DON A. OSTLER
Executive Director and Secretary

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2016WR019638

Key Points:

- Record Colorado River flow reductions averaged 19.3% per year during 2000–2014. One-third or more of the decline was likely due to warming
- Unabated greenhouse gas emissions will lead to continued substantial warming, translating to twenty-first century flow reductions of 35% or more
- More precipitation can reduce the flow loss, but lack of increase to date and large megadrought threat, reinforce risk of large flow loss

Supporting Information:

- Supporting Information S1

Correspondence to:
B. Udall,
Bradley.udall@Colostate.edu

Citation:
Udall, B. and J. Overpeck (2017), The twenty-first century Colorado River hot drought and implications for the future, *Water Resour. Res.*, *53*, 2404–2418, doi:10.1002/2016WR019638.

Received 14 AUG 2016
Accepted 14 FEB 2017
Accepted article online 17 FEB 2017
Published online 24 MAR 2017

The twenty-first century Colorado River hot drought and implications for the future

Bradley Udall[1,2] and Jonathan Overpeck[2,3]

[1]Colorado Water Institute, Colorado State University, Fort Collins, Colorado, USA, [2]Colorado River Research Group, Boulder, Colorado, USA, [3]Department of Geosciences and Department of Hydrology and Atmospheric Sciences, Institute for the Environment, University of Arizona, Tucson, Arizona, USA

Abstract Between 2000 and 2014, annual Colorado River flows averaged 19% below the 1906–1999 average, the worst 15-year drought on record. At least one-sixth to one-half (average at one-third) of this loss is due to unprecedented temperatures (0.9°C above the 1906–1999 average), confirming model-based analysis that continued warming will likely further reduce flows. Whereas it is virtually certain that warming will continue with additional emissions of greenhouse gases to the atmosphere, there has been no observed trend toward greater precipitation in the Colorado Basin, nor are climate models in agreement that there should be a trend. Moreover, there is a significant risk of decadal and multidecadal drought in the coming century, indicating that any increase in mean precipitation will likely be offset during periods of prolonged drought. Recently published estimates of Colorado River flow sensitivity to temperature combined with a large number of recent climate model-based temperature projections indicate that continued business-as-usual warming will drive temperature-induced declines in river flow, conservatively −20% by midcentury and −35% by end-century, with support for losses exceeding −30% at midcentury and −55% at end-century. Precipitation increases may moderate these declines somewhat, but to date no such increases are evident and there is no model agreement on future precipitation changes. These results, combined with the increasing likelihood of prolonged drought in the river basin, suggest that future climate change impacts on the Colorado River flows will be much more serious than currently assumed, especially if substantial reductions in greenhouse gas emissions do not occur.

Plain Language Summary Between 2000 and 2014, annual Colorado River flows averaged 19% below the 1906–1999 average, the worst 15-year drought on record. Approximately one-third of the flow loss is due to high temperatures now common in the basin, a result of human caused climate change. Previous comparable droughts were caused by a lack of precipitation, not high temperatures. As temperatures increase in the 21st century due to continued human emissions of greenhouse gasses, additional temperature-induced flow losses will occur. These losses may exceed 20% at mid-century and 35% at end-century. Additional precipitation may reduce these temperature-induced losses somewhat, but to date no precipitation increases have been noted and climate models do not agree that such increases will occur. These results suggest that future climate change impacts on the Colorado River will be greater than currently assumed. Reductions in greenhouse gas emissions will lead to lower future temperatures and hence less flow loss.

1. Introduction

A large number of studies over the last 25 years have considered the future runoff of the Colorado River (Figure 1) under climate change. Nearly all of these studies have cautioned that future warming will deplete the flow of the river, but the results have varied from minor to major [*Nash and Gleick*, 1991; *Christensen et al*., 2004; *Milly et al*., 2005; *Brekke et al*., 2007; *Christensen and Lettenmaier*, 2007; *National Research Council*, 2007; *Seager et al*., 2007; *Barnett and Pierce*, 2008; *Ray et al*., 2008; *Barnett and Pierce*, 2009; *Rajagopalan et al*., 2009; *Cayan et al*., 2010; *Reclamation*, 2013; *Harding et al*., 2012; *Seager et al*., 2012; *Vano et al*., 2012; *Ficklin et al*., 2013; *Vano et al*., 2014; *Ayers et al*., 2016; *Milly and Dunne*, 2016]. In contrast, the latest U.S. Government assessment implies little or no change is likely because precipitation increases will be sufficient to maintain temperature-depleted flows [*Reclamation*, 2016]. Fifteen years into the twenty-first century, the emerging reality is that climate change is already depleting

AGU Water Resources Research 10.1002/2016WR019638

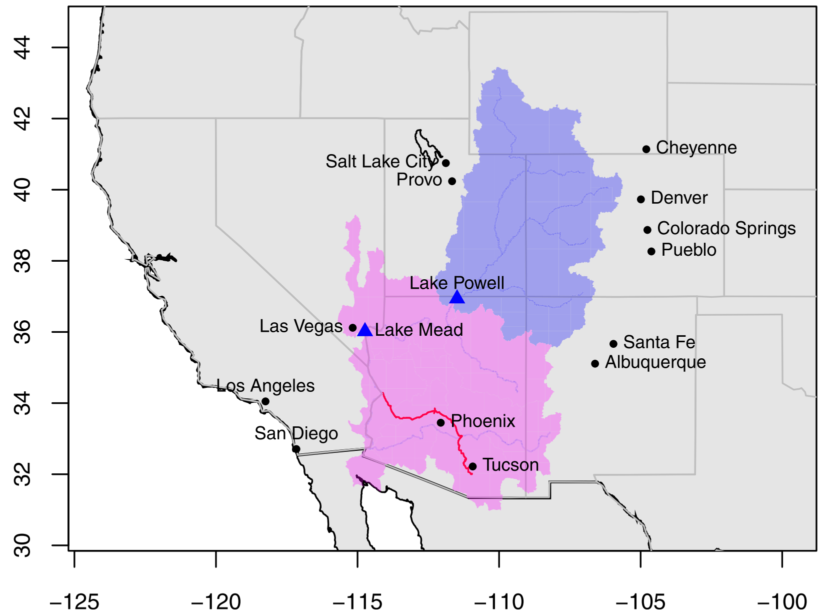


Figure 1. Map of the Colorado River Basin. Lower and Upper Basins, major U.S. cities receiving Colorado River water, major tributaries, and Lakes Mead and Powell are shown. The Central Arizona Project canal in red.

Colorado River water supplies at the upper end of the range suggested by previously published projections. Record setting temperatures are an important and underappreciated component of the flow reductions now being observed.

Between the start of the drought in 2000 and the end of 2014, our analysis period, annual flow reductions averaged 19.3% below the 1906–1999 normal period, and Lakes Mead and Powell, the nation's two largest reservoirs, ended the period at approximately 40% of maximum volume despite starting the period nearly full [*Wines*, 2014; *Colorado River Basin Stakeholders*, 2015] (Figure 2a). This drought has continued into 2015 and 2016 with higher, but still below normal, flows estimated at 94% in 2015 and 94% in 2016 with unusual late season May and June precipitation in both years that raised runoff by nearly 20% [*Alcorn*, 2015, 2016]. Despite these smaller recent reductions, Lake Mead continues to decline and in May 2016 it hit a level not seen since its initial filling in the 1930s [*James*, 2016]. The overall Colorado River reservoir system stores 4 times the annual flow of the river, one of the largest ratios in the world. This storage provides a large drought buffer when full. However, when the reservoirs are low, shortage risk can be high for years because high demands, now equal to twentieth century average flow, make it difficult to refill system storage [*Reclamation*, 2012]. While the multiyear California drought has been garnering more national attention, the more slowly unfolding Colorado River drought is every bit as serious and also has national and international ramifications [*Wines*, 2014].

The Colorado River Basin encompasses seven states and northern Mexico and is home to 22 federally recognized tribes. The river provides municipal and industrial water for 40 m people distributed across every major Southwestern city both within and without the basin, including Los Angeles, San Diego, Las Vegas, Phoenix, Tucson, Salt Lake City, Denver and the entire Front Range of Colorado, Albuquerque, and Santa Fe [*Reclamation*, 2012].

Continued low flows would result in additional declines at Lake Mead, eventually requiring Lower Basin (Arizona, California, Nevada) water delivery shortages with mandatory cutbacks imposed primarily on Arizona, but also Nevada and Mexico [*Verburg*, 2011]. At the same time, Upper Basin (Colorado, New Mexico, Utah, Wyoming) water users would continue to endure physical shortages from a lack of water. These initial Lower Basin Lake Mead delivery shortages and Upper Basin physical shortages are manageable to a point; however, under current operating rules with continued low flows during the next 6 to 8 years Lake Mead would drop to elevation 305 m (1000 feet) above sea level, resulting in a number of serious and unprecedented problems [*Collum and McCann*, 2014].

In the Lower Basin, Arizona could theoretically lose its water allocation for the entire Central Arizona Project canal, a critical $4.4B, 530 km cross-state 2 bcm/yr water source for 4.7 m people, multiple sovereign Indian

AGU Water Resources Research 10.1002/2016WR019638

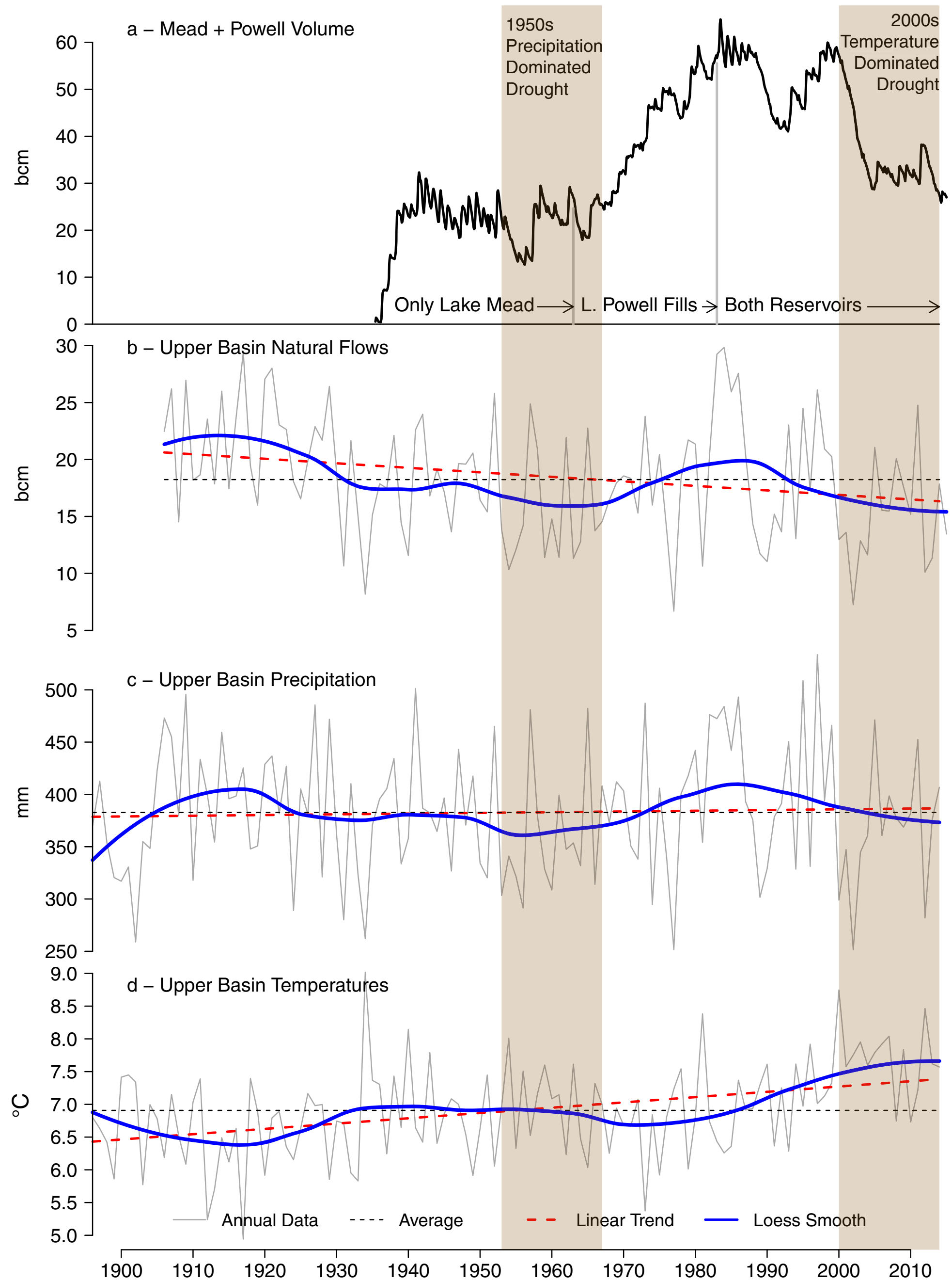


Figure 2. (a) Lakes Mead and Powell combined monthly contents. Upper Basin annual Colorado River (b) runoff at Lees Ferry from 1906 to 2014, (c) precipitation and (d) temperatures from 1896 to 2014. Mead first filled in 1935, Powell in 1963 (supporting information Text S1). Two 15-year drought periods, 1953–1967 and 2000–2014, are highlighted and discussed in main text.

nations, and over 120,000 irrigated hectares [*Glennon*, 1995; *Colorado River Basin Stakeholders*, 2015]. This canal currently relies on occasional but uncertain "equalization" releases from Lake Powell that only occur with irregular and rare large Powell inflows. The extra water is delivered when Lake Powell reaches levels substantially higher than Lake Mead, a use allowed under the 1922 Colorado River Compact section III (e) and formalized most recently under rules established in a 2007 Record of Decision for coordinated operations of Lakes Powell and Mead and for shortage sharing in the Lower Basin [*Department of Interior*, 2007].

Under normal operating rules, without these extra inflows, Lake Mead has excess outflows of 1.5 bcm per year, the so-called Lower Basin "structural deficit" [*Collum and McCann*, 2014]. The structural deficit was created in 1968 when Congress authorized the Central Arizona Project (CAP). In order to obtain the support of

AGU Water Resources Research 10.1002/2016WR019638

the large California Congressional delegation, Arizona agreed to rely on this unused, but in the long run unreliable water, because there was not enough remaining unallocated Lower Basin water. The CAP had long been a desire of Arizona and the state was willing to make this bargain despite its flaws [*Johnson*, 1977]. This same water is first available for use by the Upper Basin under the Colorado River Compact, but heretofore has not been developed for Upper Basin use. A plan to augment the Colorado River with flows from outside the basin, discussed during the hearings on the legislation, but not included in the final package due to opposition from potential source areas, was never revisited by Congress. Reclamation in 2011 said that such augmentation was now unlikely.

The structural deficit only became a problem when the CAP was fully completed in the mid-1990s combined with the drought that began in 2000. Upper Basin demand growth has also played a small role, although Upper Basin demands are still much less than forecast in 1968 for the year 2000 [*Tipton and Kalmbach, Inc*., 1965; *Johnson*, 1977]. The recent Lake Mead declines are strongly influenced by this imbalance, and solutions to this deficit have been a recent focus of the Basin states and federal government [*Central Arizona Project*, 2016; *Davis*, 2016].

The Upper Basin also has serious issues, one of which ripples into the Lower Basin. When the surface of Lake Mead declines to an elevation 305 m (1000 feet) above sea level, Lake Powell will also be below its minimum power pool 75% of the time [*Collum and McCann*, 2014]. This occurs in part because low Mead levels make "equalization" releases from Powell more likely thus driving Powell lower. Hydropower losses at Lake Powell could result in substantial rate increases for irrigators who rely on the reservoirs for long term lower cost power contracts, and would also dry up funding for basin-wide programs necessary for water delivery environmental compliance [*Adler*, 2007; *Collum and McCann*, 2014]. Under such low reservoir conditions, there is also a high likelihood that the Upper Basin states would have to curtail existing water deliveries to cities such as Denver, Colorado Springs, Albuquerque and Salt Lake City in order to make required deliveries to Lake Mead. Heretofore, largely because of the structure of the Colorado River Compact, the Upper Basin and Lower Basin have been managed separately. With permanent flow declines of approximately 20%, however, the required deliveries to Lake Mead would become a hardship on the Upper Basin, as well as create Lower Basin delivery shortages [*Reclamation*, 2007; *Barnett and Pierce*, 2009; *Rajagopalan et al*., 2009]. The original compact, signed during one of the wettest periods in the last 450 years [*Woodhouse et al*., 2006], did not envision how large scale flow declines would be managed between the basins, and such declines could cause an allocation crisis between the Upper and Lower Basins [*Adler*, 2008].

Understanding the cause of, and reacting properly to, the ongoing drought is critical to the future of the Southwest. Herein we investigate the role of precipitation versus temperatures as causes of the current drought, provide temperature-based and precipitation-based twenty-first century flow projections and provide policy implications of these findings. Our approach separates the impacts of high-confidence temperature projections from those associated with the much lower-confidence projections of future precipitation using a simple but powerful sensitivity technique. Moreover, we make a novel—and important—case that there is a high likelihood that the impacts of continued atmospheric warming will overwhelm any future increases in precipitation because prolonged dry periods lasting multiple decades are likely to negate the beneficial impacts of additional precipitation during other times.

2. Causes of the 2000–2014 Drought

The 2000–2014 drought is defined by the lowest average annual flows for any 15-year period in the historical record. To analyze this drought, gridded 4 $\times$ 4 km temperature and precipitation data from 1896–2014 for the area above Lees Ferry were obtained from the Precipitation-Elevation Regression on Independent Slopes (PRISM) model [*Daly et al*., 1994; *Guentchev et al*., 2010; *Oyler et al.,* 2015a, 2015b; *Rangwala et al.,* 2015]. In addition, we obtained reservoir contents and natural flows at Lees Ferry from the U.S. Bureau of Reclamation (Reclamation) (Text S1). Lees Ferry is situated just below Lake Powell and is the Compact dividing line between the Upper and Lower Basins. Approximately 85% of the flow originates above Lees Ferry [*Christensen and Lettenmaier*, 2007].

Historically, Upper Colorado River Basin precipitation has been the main Colorado River runoff driver such that high flow years (1920s, 1980s) were associated with high precipitation and low flow years (1930s, 1950s) with low precipitation (Figures 2b and 2c). The current drought (our study period is 2000–2014, but

AGU Water Resources Research 10.1002/2016WR019638

Table 1. Winter/Summer/Annual Upper Basin Mean Water Year Precipitation

	1953–1967			2000–2014			1896–2014	
	mm			mm			mm	
	Total	Anomaly	Anomaly % of Mean (%)	Total	Anomaly	Anomaly % of Mean (%)	Mm	% Avg
Winter (Oct to Mar)	176	−16	−8.6	187	−5	−2.7	192	100
Summer (Apr to Sep)	184	−7	−3.6	179	−12	−6.4	191	100
Total	359	−23	−6.1	365	−17	−4.6	383	100

the drought is still on-going), with its modest −4.6% precipitation decline and −19.3% flow decline, stands in stark contrast to the second-lowest 15-year flow period (1953–1967), a precipitation-driven drought with averaged precipitation reductions of −6.1% per year and flow reductions of −18.1% per year (Figures 2b and 2c and Table 1). Compared to the 1950s drought, the 2000s feature much more (near normal) winter precipitation (−8.6% 1950s decline versus −2.7% 2000s) and significantly less summer precipitation (−3.6% 1950s decline versus −6.4% 2000s). The 2000s precipitation decline is only 75% of the decline in the 1950s, thus begging the question of why the recent drought was more serious. What has changed is that temperatures in the runoff producing Upper Basin are now 0.9°C above the 1896–1999 average and are the highest in the gaged record; whereas temperatures during the 1953–1967 drought were much cooler and only slightly above the 1896–1999 average (Figure 2d and Table 2). This makes the current drought unprecedented in the gaged record.

In contrast to the more precipitation-driven current California drought [*Diffenbaugh et al.*, 2015; *Williams et al.*, 2015], lack of precipitation is only partially to blame for the Colorado River runoff declines during the last 15 years. Instead, approximately a third, or more, of the recent Colorado River flow reduction is most likely a result of record-setting warmth. Since 1988 an increase in the frequency of warm years has been strongly associated with lower flows than expected [*Woodhouse et al.*, 2016], suggesting an important role for temperature in flow losses. Such temperature-driven droughts have been termed "global-change type droughts" and "hot drought," with higher temperatures turning what would have been modest droughts into severe ones, and also increasing the odds of drought in any given year or period of years [*Breshears et al.*, 2005; *Overpeck*, 2013]. Higher temperatures increase atmospheric moisture demand, evaporation from water bodies and soil, sublimation from snow, evapotranspiration (ET) from plants, and also increase the length of the growing season during which ET occurs [*Pitman*, 2003; *Weiss et al.*, 2009; *Seneviratne et al.*, 2010; *Seager et al.*, 2015a]. Warm season (April to September) warming has been identified by models as especially important in reducing Colorado River flows because of the increases in ET from longer growing seasons [*Das et al.*, 2011]. Increases in measured vapor pressure deficits in the Southwest caused by warming and a decrease in water vapor provide strong support for higher ET during the recent drought [*Seager et al.*, 2015b]. As increasing temperatures drive further drying, additional positive feedbacks are possible in the form of lower humidity and less evaporative cooling, decreased cloudiness and increased incident radiation, as well as decreased snow cover and more radiative heating [*Betts et al.*, 1996; *Brubaker and Entekhabi*, 1996; *Pitman*, 2003; *Seneviratne et al.*, 2010]. In the twentieth century, droughts were associated almost exclusively with a lack of precipitation. In this century, however, high temperatures alone can lead to anomalously dry conditions.

Table 2. Upper Basin Water Year Flows and Temperatures

	Average Annual Flow		Average Annual Temperature	
Period	bcm	% 1906–1999	°C	°C Anomaly to 1896–1999
1953–1967	15.38	81.9	7.0	0.2
2000–2014	15.15	80.7	7.7	0.9
1906–1999	18.77	100.0	6.8	0.0
1906–2014	18.27	97.3	6.9	0.1

3. Estimates of 2000–2014 Temperature-Induced Flow Loss

Over the last several years several studies specific to the Colorado River Basin have investigated the specific relationships among temperatures, precipitation and flow in the basin using the concepts of temperature

AGU Water Resources Research 10.1002/2016WR019638

sensitivity and precipitation elasticity [*McCabe and Wolock*, 2007; *Nowak et al*., 2012; *Vano et al*., 2012, 2014; *Vano and Lettenmaier*, 2014]. Temperature sensitivity is defined as the percent change in annual flow per degree rise in annual temperature. Precipitation elasticity is defined as the fractional change in annual flow divided by the fractional change in annual precipitation [*Vano et al*., 2012]. Note that elasticity has been studied for both increases and decreases in precipitation, whereas sensitivity is typically investigated only for temperature increases. These numbers can be determined empirically and through model studies.

Previous studies on temperature sensitivity and precipitation elasticity show that future impacts to streamflow from increases in temperatures and changes in precipitation can be considered separately using sensitivity and elasticity, and then added together to produce flow estimates [*Vano et al*., 2014; *Vano and Lettenmaier*, 2014]. Considering these effects separately and additively is a powerful conceptual tool for investigating climate change impacts because of the ease in measuring the two variables for current impacts and the wide availability of temperature and precipitation projections from global climate models for assessing future impacts. In addition, the large differences in certainty associated with future changes in the two variables (temperature will surely increase, whereas precipitation may increase or decrease—see below) helps to set apart the risk of future changes in flow associated with each variable.

Vano et al. [2012, 2014], *McCabe and Wolock* [2007], and *Nowak et al*. [2012] provide multiple estimates of the flow sensitivity of the Colorado River flow to temperature using three different methods. *Vano et al*. [2012, 2014] utilized six high-resolution, commonly used hydrology models and two different temperature adjustment methods to obtain Lees Ferry temperature sensitivities. They report an average sensitivity of −6.5%/°C warming with a one standard deviation range from −3.0% to −10.0%/°C for the Upper Basin. Approximately 50% models show increasing sensitivity and 50% decreasing sensitivity as temperatures warm so we elect to use a constant sensitivity over all future temperatures. *McCabe and Wolock* [2007] constructed a simple water balance model that infers an average temperature sensitivity of −8.9%/°C and *Nowak et al*. [2012] found an empirical temperature sensitivity of −13.8%/°C.

We use the complete one standard deviation range (−3%/°C to −10%/°C) of the *Vano et al*. [2012, 2014] temperature sensitivity estimates as they were the most conservative and rigorous of the three studies we investigated. Using this range, we found that recent warming of 0.9°C has likely already reduced river flows from −2.7% to −9% from the mean 1906–1999 flow. This represents approximately one-sixth to one-half (average of one-third) of the total flow loss during the 2000–2014 drought.

The higher temperature sensitivities of the two other studies suggest the actual Colorado River temperature sensitivities are near the upper end and possibly exceed the *Vano et al*. [2012, 2014] estimates. These higher sensitivities imply much greater temperature-induced losses during the current drought (−7.9% to −12.3% versus −2.7% to −9%). Empirical results from the 2000 to 2014 drought also point to mid to high temperature sensitivities. *Vano et al*. [2012] report precipitation elasticities ranging from 2 to 3 at Lees Ferry. Thus, using a midrange precipitation elasticity of 2.5, the 2000–2014 annual −4.6% precipitation decline implies runoff reductions of −11.4%, leaving the remaining −7.9% decline to be explained by other causes. If temperature were the sole cause of this remaining decline, the inferred temperature sensitivity is −8.8%/°C. Using a precipitation elasticity of 3.0 implies a temperature sensitivity of −6.2%/°C, very close to the midrange Vano et al., sensitivity. These temperature sensitivities imply large losses as temperatures rise, the subject of the next section.

4. Twenty-First Century Flow Response to Changing Temperatures and Precipitation

For the analysis on how future temperatures and precipitation would affect runoff, and for investigating how well current linked climate-hydrology models can reproduce the current drought, we used Reclamation's climate projection data sets [*Brekke et al*., 2013, 2014]. These data sets use Coupled Model Intercomparison Project 3 and 5 (CMIP3, CMIP5 after the class of climate models used) climate model projection data linked to the Variable Infiltration Capacity hydrology model to produce flows from 1950 to 2099 (supporting information Text S2, Figures S2, and S3)] [*Liang et al*., 1996; *Meehl et al*., 2007; *Moss et al.,* 2010; *Taylor et al*., 2012].

The same temperature sensitivity and precipitation elasticity numbers discussed above can be used to estimate future flow reductions using climate model outputs under high (business-as-usual, SRES A2 and

AGU Water Resources Research 10.1002/2016WR019638

RCP8.5) and moderate (somewhat reduced by mitigation, SRES A1B and RCP4.5) greenhouse gas emissions to the atmosphere. By 2050, moderate and high emissions are projected to yield Upper Basin *mean* warming of 2.6–2.8°C (Figure 3), three times recent warming, and by 2100, warming of 3.6°C under moderate emissions and 5.4°C under high emissions. This warming implies total multimodel mean temperature-induced flow losses at midrange sensitivity of −6.5%/°C of about −17% by midcentury and −25% to −35% at end-century (Figures 4 and 5). The multimodel mean complete flow loss *range* over both periods and both emissions is approximately −8% to −55% using the lower and upper temperature sensitivities (Figures 4 and 5). As discussed above, there is little empirical evidence that the true temperature sensitivity of flow to temperature increase is near the low sensitivity.

Temperature-induced losses may be somewhat buffered by projected additional precipitation that can increase runoff by 2–3% for every 1% change in precipitation [*Vano et al.*, 2012]. At midcentury precipitation increases of +4–+11% given a midrange elasticity of 2.5 would balance the range of temperature-induced flow losses at a midrange—6.5%/°C sensitivity (Figure 5, right *y* axis). At end-century, with the same sensitivity and elasticity, additional precipitation increases of +4–+20% would balance the range of possible temperature-driven losses. At a higher −10%/°C sensitivity, the balancing precipitation would need to be as great as +15% or more at midcentury and +22% or more at end-century. While these may seem like relatively small increases in precipitation, and thus possible, they would represent a major and unprecedented change in precipitation regime compared to the observed historical variation in precipitation (Figure 2c). During the twentieth century, for example, the wettest 10-year period (1983–1997) had only a +8% precipitation increase. This unusual period was marked by major floods downstream of Lakes Powell and Mead due to uncontrolled reservoir spilling and the near catastrophic loss of the spillways at Glen Canyon Dam [*Udall*, 1983].

Vano and Lettenmaier [2014] argue that the sensitivity-based approach used in our projections provides similar estimates of future streamflow to those generated with more computationally intensive coupled-model methods, except for some (i.e., 10%) overstatement of flow reductions at the highest levels of possible warming by 2100 (e.g., the business-as-usual SRES A2 scenario used in the CMIP3 projections and the RCP8.5 in the CMIP5 projections). This would reduce the end of century high emissions mean flow reductions shown in Figure 5 to a still very significant −45% by 2100.

Recent studies have suggested that CO_2 fertilization may increase plant water efficiency thus reducing future evapotranspiration which could serve to mitigate our projected losses [*Milly and Dunne*, 2016; *Swann et al.*, 2016]. Both studies call into question results that show large portions of the globe drying in the twenty-first century [e.g., *Dai*, 2012; *Cook et al.*, 2014]. However, *Milly and Dunne* [2016] and *Swann et al.* [2016] show that, despite this increase in plant water use efficiency, the Southwestern US will still dry, a finding that is consistent with multiple global assessments showing substantial drying risk to midlatitude areas such as the Colorado River Basin. Moreover, a recent Australian study found that higher

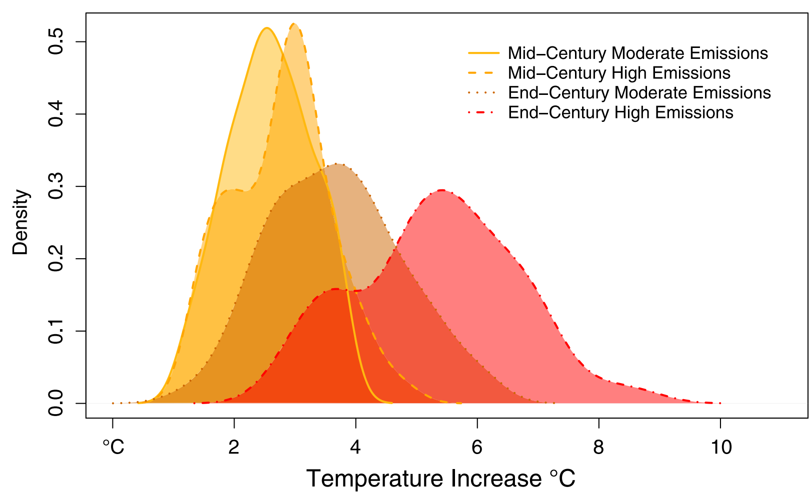


Figure 3. Probability density functions of Upper Colorado River Basin temperature projections for midcentury and end-century under moderate (SRES A1B and RCP4.5) and high (SRES A2 and RCP8.5) emissions.

AGU Water Resources Research 10.1002/2016WR019638

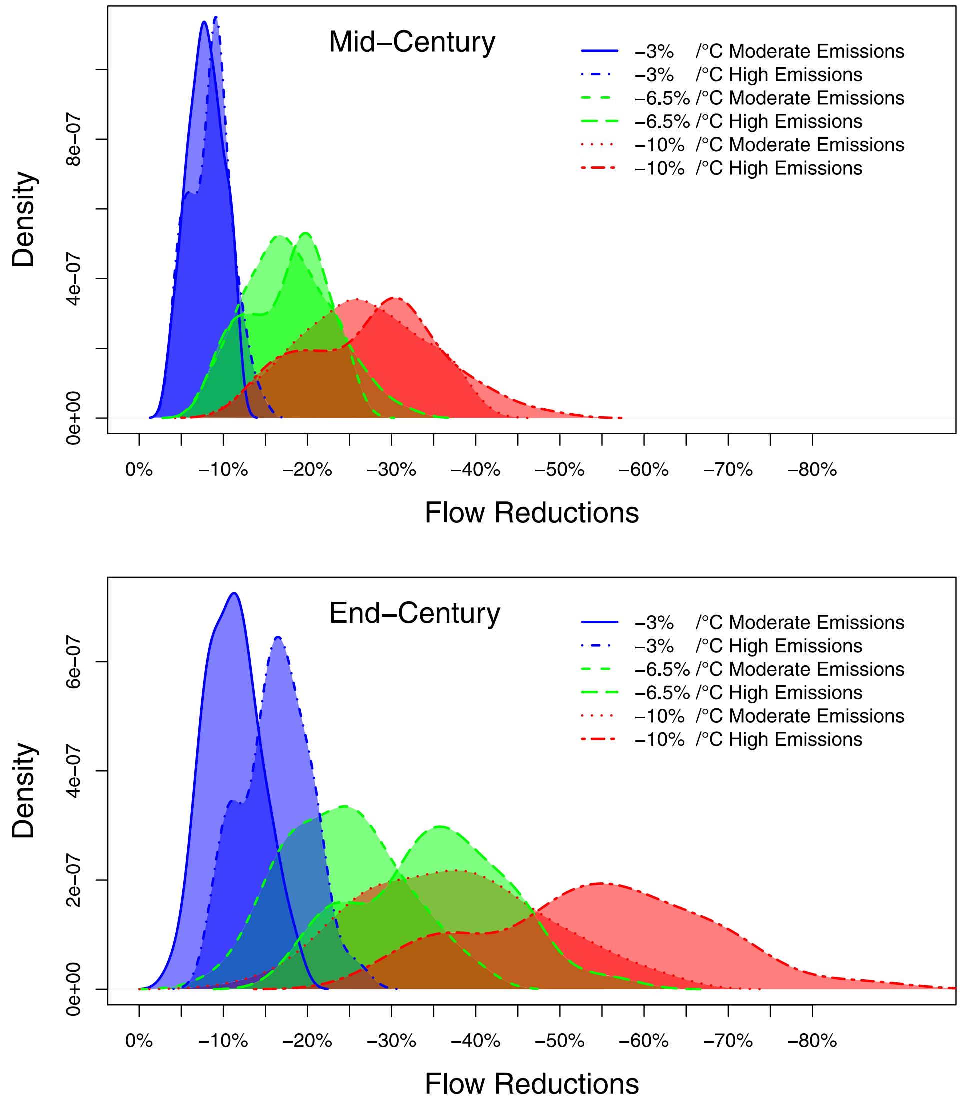


Figure 4. Probability density functions of Upper Colorado River Basin temperature-induced flow reductions for midcentury and end-century with the three temperature sensitivities (−3%, −6.5%, −10%) and the two levels of emissions (Moderate: SRES A1B and RCP4.5 and High: SRES A2 and RCP8.5).

evapotranspiration associated with the increased plant growth stimulated by higher CO_2 outweighed any CO_2-related water-use efficiency effect, and served to reduce streamflows in semiarid regions [*Ukkola et al.*, 2015], a trend that must be exacerbated by the temperature-induced lengthening of the growing season. These results suggest that plant physiological responses are likely consistent with our results, and in any case, do not invalidate them.

5. Megadrought Risks to Flows

Megadroughts lasting decades in the Colorado River Basin have occurred in the past, with resulting substantial flow reductions [*Meko et al.*, 2007]. Multiple papers now suggest there is high twenty-first century risk for megadrought in the American Southwest and that the risk will increase as temperatures rise [*Ault et al.*, 2014; *Cook et al.*, 2015; *Ault et al.*, 2016]. In addition, current GCMs underrepresent the frequency of megadrought [*Ault et al.*, 2012, 2013]. These findings provide additional support for large flow reductions during at least multidecadal drought periods and suggest that current twenty-first century flow projections underrepresent this risk.

Significant Colorado River flow losses occurred during previous multidecadal megadroughts. During the twelfth century, flow reductions of approximately −16% occurred during one 25-year period [*Meko et al.*,

AGU Water Resources Research 10.1002/2016WR019638

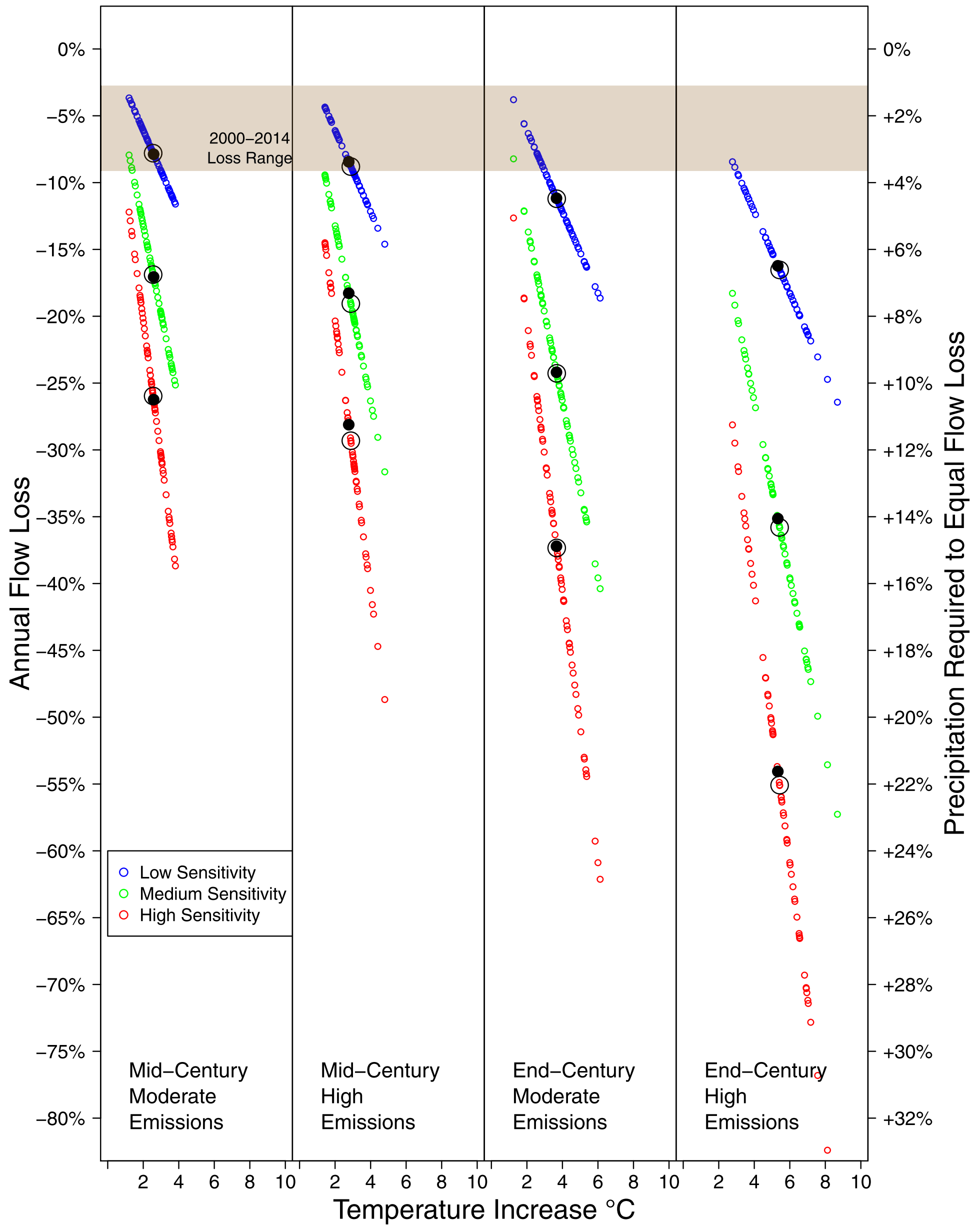


Figure 5. Temperature-induced flow losses by model run (one per dot) with temperature increases shown on horizontal axis. For each period (midcentury, end-century) and emissions type (moderate, high), flow losses for each model run are shown with the 3 (low = −3%/°C, medium = −6.5%/°C, high = −10%/°C) temperature sensitivities. Black dots/circles are averages/medians for each sensitivity. Precipitation increases needed to counteract flow losses at right are based on 2.5 precipitation elasticity. Range for the temperature-induced losses during 2000–2014 drought are shown in shaded brown at the top (supporting information Text S5).

2007]. Evidence indicates that hemispheric and Southwest temperature anomalies were significantly smaller during past megadroughts than the rapid on-going current warming that could easily exceed 4–5°C by the end of century under business-as-usual emissions [*Salzer and Kipfmueller*, 2005; *Mann et al.*, 2009; *Salzer et al.*, 2014] (Figure 5). Using the additivity concepts discussed above, additional warming of 1°C, 2°C, or 3°C beyond the historic twelfth century megadrought temperatures would have reduced the −16% flow declines by an additional −6.5%, −13%, or −19.5% at medium temperature sensitivity. These additional reductions would have thus turned a −16% flow decline into declines of −21.5%, −28%, or −34.5%, losses near the middle of our projections.

There is recent strong evidence that continued warming over the next 80 years could increase the risk of multidecadal drought [*Ault et al.*, 2014, 2016; *Cook et al.*, 2015]. Independent of the added drought risk due

AGU Water Resources Research 10.1002/2016WR019638

to continued warming, the risk of a 35-year precipitation-deficit drought later in this century exceeds 15% within a 50-year period [*Ault et al*., 2014]. In contrast, with continued anthropogenic warming, the risk of multidecadal megadrought in the Southwest increases to over 90% over this century if there is no increase in mean precipitation; even if modest precipitation increases do occur, the risk will still exceed 70% [*Ault et al*., 2014, 2016]. At medium warming (4°C), 20–30% precipitation increases will be needed to reduce megadrought risk below 50% and at high amounts of warming (>6°C), it will take a ~40% increase in precipitation to reduce megadrought risk below 50% [*Ault et al*., 2016]. These changes in precipitation are huge and unlikely, and they would still only reduce megadrought risk to below 50%.

Both the CMIP3 and CMIP5 Global Climate Models may not adequately reproduce the frequency of occurrence of known past decadal and multidecadal precipitation droughts [*Ault et al*., 2012, 2013]. In the Colorado River Basin empirical evidence of this problem can be found in the linked GCM-hydrology model results from Reclamation's projections for the basin [*Brekke et al*., 2014]. Approximately half of the CMIP5 models and one-quarter of the CMIP3 models cannot simulate the 2000–2014 drought at any point in the twenty-first century (supporting information Text S3 and Tables S1–S4). This wet bias significantly affects the mean flows of drought-capable and nondrought capable models. At the end of the twenty-first century, the models unable to simulate the current drought are much wetter (109% of twentieth century average Lees Ferry runoff for CMIP3, 113% for CMIP5) than the models that are able to simulate the current drought (85% of average runoff for CMIP3, 91% CMIP5) (supporting information Tables S1–S4). These flow differences are greater than 20%, and represent the difference between serious management challenges and significant oversupply.

6. Risk-Based Framing of Future Runoff Projections

At present, some outputs from global climate models are ready to support reliable risk-based policy while others are not as ready. A key novel aspect of our research is to provide more insight into where confidence is warranted, and where it is not, with respect to projections of future climate and flow change in the Colorado River Basin. In the case of the Basin, every single moderate and high emissions model simulation agrees that temperatures will continue to rise significantly with continued emissions of greenhouse gases to the atmosphere—this result is robust, highly certain and well-suited for informing policy choices. The fact that observations also show substantial warming only strengthens this assertion.

On the other hand, simulated future precipitation change in the Basin is clouded with much greater uncertainty due to substantial disagreement among models and a highly uncertain ability to simulate realistic change in key phenomena such as storm-track position or decadal and longer-scale drought. Whereas climate models are in general agreement that cool season (warm season much less certain) precipitation declines are likely in the Lower Colorado River Basin, these same models disagree when it comes to the sign and amount of precipitation change that is likely in the Upper Basin. This is because precipitation change in the Upper Basin will depend heavily on the exact changes in the position of cool season jet stream and storm-tracks, two aspects of climate change that are not simulated with confidence by global climate models [*Collins et al*., 2013].

Moreover, there is strong evidence that the mean positions of both the jet stream and storm-tracks are likely to push poleward, expanding the area of aridity in the Colorado River Basin, but the amount of this expansion is poorly constrained [*Collins et al*., 2013]. Multiple studies, including some focused on the American Southwest, suggest that the proximate cause of this drying, Hadley Cell expansion, is already well underway and will continue [*Seager et al*., 2007; *Scheff and Frierson*, 2012; *Feng and Fu*, 2013; *Norris et al*., 2016; *Prein et al*., 2016].

Our results regarding future changes in Colorado River flows agree with many previous studies in suggesting climate change translates to flow reductions, although our work is generally not directly comparable because we separate out high confidence temperature-related impacts from the possible effects of much less certain and highly variable precipitation projections. However, our work, as well as this larger body of literature, appears to be at odds with the recent Reclamation projections for the Colorado River Basin, which are widely cited and used. Reclamation's projections use a global climate model output that is downscaled to drive a hydrology model. It is worth understanding why our results emphasize substantially greater risks along with apparently greater flow losses.

AGU Water Resources Research 10.1002/2016WR019638

The 2011 CMIP3 climate change flow projections by Reclamation indicate a modest multimodel median flow decline of −9% by 2060 for the river, but with a wide range of outcomes from flow increases to flow decreases [*Reclamation*, 2012] (supporting information Table S1). Reclamation's most recent CMIP5 projections show no change in mean and median basin-wide flow by 2070s [*Reclamation*, 2016], but also embody a wide range of results. Compared to CMIP3, the CMIP5 results show increased precipitation, especially in the northern parts of the basin including Northeast Utah, Northwest Colorado's Yampa River and the Green River in Wyoming [*Brekke et al*., 2014; *Ayers et al*., 2016] (supporting information Tables S1 and S3). The increased precipitation in the CMIP5 model runs compared to CMIP3 can be attributed to more southerly storm tracks in CMIP5 that occur in late spring [*Brekke et al*., 2014].

Another issue arises in both the CMIP3 and CMIP5 data sets when GCM precipitation is adjusted by the downscaling techniques necessary for off-line hydrology models. The first step in Reclamation's downscaling is a bias correction step. This step can add approximately 5% more precipitation to the raw GCM precipitation, and this increase appears to not have a physical basis [*Reclamation*, 2013; *Brekke et al*., 2013]. The final downscaling step, spatial downscaling, also increases GCM precipitation, although there is at least a plausible physical explanation for some of the increase: higher elevations in the Rockies receive large amounts of precipitation, but these elevations are not properly modeled by the GCMs. In one study of the CMIP5 data set after downscaling, dry and average models show precipitation increases of approximately +∼5% from the raw GCM output, but the wettest models show +∼10% increases, doubling future precipitation increases from +10% to +20% [*Lukas et al*., 2014]. This extra precipitation is manifested in a number of hydrology model runs that project huge and implausible flow increases in some years that are 150% of the highest known flows in the twentieth century (supporting information Text S4, Figures S2, and S3). The downscaling wetness problem has been identified, but has not been not resolved [*Lukas et al*., 2014]. Reclamation acknowledges that the newer CMIP5 projections have not been determined to be better or more reliable [*Brekke et al*., 2014]. It is noteworthy that internally consistent GCM-only Southwest runoff projections almost uniformly produce significant declines in both CMIP3 and CMIP5 runs [*Milly et al*., 2005; *Seager et al*., 2007, 2012; *Koirala et al*., 2014; *Milly and Dunne*, 2016].

Our results are generally comparable to Reclamation's most recent results when considering the full range of our analysis when both precipitation and temperatures are included. However, our focus and emphasis is on the large near-certain temperature-induced flow declines with a separate analysis of precipitation. Reclamation, by contrast, has a focused on climate multimodel-ensemble median declines, including medians calculated across emission scenarios [*Reclamation*, 2013, 2012]. Decision makers often treat these median outcomes as a proxy for risk despite the fact that the median obscures the wide range of results and lumps wet and dry, warm and hot, large and small emission increases and, most critically, near certain temperature increases and very uncertain precipitation changes.

We assert that the large precipitation increases necessary to offset substantial temperature-induced flow decreases appear unlikely to occur for a number of reasons. These reasons include the potential for storm tracks to go north of the basin due to Hadley Cell expansion, the high potential for megadrought to increase evaporation while reducing precipitation and runoff for extended periods, the large size of the needed precipitation increases, especially when compared to decadal historical increases, the consistent identification by global assessments of the Southwest as an area likely to dry, and finally the lack of any trend over the last century or last 16 years (Figure 2c). Hence, we choose to focus on highly likely temperature-induced declines with separate analysis of the precipitation needed to offset these declines.

7. Policy Implications and Solutions

The climate science take-home messages for Colorado River managers are thus: (1) there is little doubt (i.e., high confidence) that temperatures will continue to increase as long as the emissions of greenhouse gases to the atmosphere continue; (2) there is also high confidence that continued temperature increases will cause river flows to decline, ranging from −11% to as much as −55% by end of century under moderate to high emissions (Figures 4 and 5); (3) there is only low confidence associated with the possibility of storms and precipitation in the Upper Basin increasing enough to even partially offset the temperature-driven declines in river flows; (4) the risk of multidecadal megadrought in the Basin is significant even in the absence of continued anthropogenic climate change, and this risk rises substantially with continued global

AGU Water Resources Research 10.1002/2016WR019638

warming; (5) the likelihood of drought and megadrought means that there will likely be decades-long periods with anomalously low runoff even if there is an increase in precipitation relative to the historical mean during some other periods due to anthropogenic climate change.

Temperature-driven threats to the flows of the Colorado are thus large and real. The only way to curb substantial risk of long term mean declines in Colorado River flow is thus to work toward aggressive reductions in the emissions of greenhouse gases into the atmosphere. Our work shows that modest (e.g., RCP4.5) reductions in greenhouse gas emissions, while having better outcomes than the business-as-usual future (e.g., RCP8.5), still imply large Colorado River flow losses.

The record warm nature of the on-going Colorado River drought indicates that this drought is not just a natural drought, and our work demonstrates that flows are unlikely to return to the twentieth century averages if we only wait. Unusually wet periods like the 1920s and 1990s will still continue to occur, but they will co-occur with higher temperatures that will increase water demand from plants, soil, snow, and humans.

Climate models and theory suggest that flow reductions would be more severe in the Southern portions of the Upper Colorado Basin affecting tributaries such as the San Juan, Dolores, and Gunnison more severely, with smaller impacts to more northerly tributaries such as the Yampa and Green [*Ayers et al*., 2016]. Such spatial distribution would provide additional water management challenges in that the more southerly basins have in general more people, infrastructure, and uses. Such a distribution would create new localized water supply shortages in addition to the overall basin-wide issues.

Other known threats to streamflows include the potential large scale loss of conifers [*Breshears et al*., 2005; *Adams et al*., 2009; *Allen et al*., 2010, 2015], and the impacts of dust on snow [*Painter et al*., 2010; *Deems et al*., 2013]. These factors along with the observed and projected temperature-induced Colorado River flow declines, the inability of many linked climate-hydrology models to simulate persistent droughts, and the increasing likelihood of hot drought and megadrought, all imply that future Colorado River water supply risk is high. It is imperative that decision-makers begin to consider seriously the policy implications of potential large-scale future flow declines. Stable twentieth century Colorado River flow regimes may not reoccur for many centuries—the time scale of climate system readjustment to the complete cessation of greenhouse gas emissions [*Solomon et al*., 2009; *Collins et al*., 2013].

The Colorado River declines do not stand alone as the only warming-related threat to Southwestern water supplies. The Rio Grande also has a grim prognosis [*Reclamation*, 2013; *Elias et al*., 2015]. The drought in California has garnered national attention, and multiple studies have strongly implicated increasing temperatures as a contributor to these woes [*Griffin and Anchukaitis*, 2014; *Belmecheri et al*., 2016; *Diffenbaugh et al*., 2015; *Mann and Gleick*, 2015; *Seager et al*., 2015a]. Southern California is particularly at risk, with a critical economy and a very large population, all coupled with a large reliance on both climate-threatened in-state, as well as Colorado River, water.

Adjusting to the new reality of rapid climate change will not be an easy or fast task; water management and water policy change slowly. The Colorado River is managed by a complex set of agreements, interstate compacts approved by Congress, international agreements, legislation, and court decrees set in place over the last 100 years [*Verburg*, 2011]. Most agreements were derived from twentieth century state-based negotiations with win/lose policy prescriptions that minimized basin-wide considerations of economic prosperity and potential harm [*Adler*, 2008]. None expressly includes climate change risk management, nor the provision for flow reductions that will be relentless on decadal timescales. New agreements often take years to put in place [*Department of Interior*, 2007]. The recently proposed structural deficit solution [*Central Arizona Project*, 2016], while important and laudable for the short term, will not solve the problem of large scale flow losses. With reduced water supplies, much will have to change in these agreements to address equity, economics, and social concerns on regional, state, basin-wide, and even national levels. Climate change threats to western water supplies are very real, and should prompt great concern and urgency among both water managers and the citizens of the Southwest.

Acknowledgments
We thank the U.S. Bureau of Reclamation for data assistance and comments, and M. Kelly, D. Kenney, E. Kuhn, D. Lettenmaier, J. Robison, P. Troch, and C. Woodhouse for comments and discussion. A portion of this research was supported by the Colorado Water Institute, National Science Foundation, the NOAA Climate Assessment for the Southwest, and the U.S. Geological Survey Southwest Climate Science Center. We acknowledge the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections as well as the World Climate Research Programme's Working Group on Coupled Modeling and the U.S. Department of Energy, Office of Science. The views expressed in this article are those solely of the authors. All data used in the analysis and conclusions in this paper are available from links in supporting information.

References

Adams, H. D., M. Guardiola-Claramonte, G. A. Barron-Gafford, J. C. Villegas, D. D. Breshears, C. B. Zou, P. A. Troch, and T. E. Huxman (2009), Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(17), 7063–7066.

Adler, R. W. (2007), *Restoring Colorado River Ecosystems: A Troubled Sense of Immensity*, Island Press, Wash.

Adler, R. W. (2008), Revisiting the Colorado River Compact: Time for a change, *J. Land Resour. Environ. Law*, *28*, 19.

Alcorn, B. (2015), *Colorado Basin River Forecast Center Final Reservoir Forecasts*, NOAA, Salt Lake City, Utah.

Alcorn, B. (2016), *Colorado Basin River Forecast Center Final Reservoir Forecasts*, NOAA, Salt Lake City, Utah.

Allen, C. D., et al. (2010), A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests, *For. Ecol. Manage.*, *259*(4), 660–684, doi:10.1016/j.foreco.2009.09.001.

Allen, C. D., D. D. Breshears, and N. G. McDowell (2015), On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene, *Ecosphere*, *6*(8), 129.

Ault, T. R., J. E. Cole, and S. St. George (2012), The amplitude of decadal to multidecadal variability in precipitation simulated by state-of-the-art climate models, *Geophys. Res. Lett.*, *39*, L21705, doi:10.1029/2012GL053424.

Ault, T. R., J. E. Cole, J. T. Overpeck, G. T. Pederson, S. St. George, B. Otto-Bliesner, C. A. Woodhouse, and C. Deser (2013), The continuum of hydroclimate variability in Western North America during the Last Millennium, *J. Clim.*, *26*(16), 5863–5878, doi:10.1175/JCLI-D-11-00732.1.

Ault, T. R., J. E. Cole, J. T. Overpeck, G. T. Pederson, and D. M. Meko (2014), Assessing the risk of persistent drought using climate model simulations and paleoclimate data, *J. Clim.*, *27*(20), 7529–7549, doi:10.1175/JCLI-D-12-00282.1.

Ault, T. R., J. S. Mankin, B. I. Cook, and J. E. Smerdon (2016), Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest, *Sci. Adv.*, *2*(10), e1600873, doi:10.1126/sciadv.1600873.

Ayers, J., D. L. Ficklin, I. T. Stewart, and M. Strunk (2016), Comparison of CMIP3 and CMIP5 projected hydrologic conditions over the Upper Colorado River Basin, *Int. J. Climatol.*, *36*(11), 3807–3818, doi:10.1002/joc.4594.

Barnett, T. P., and D. W. Pierce (2008), When will Lake Mead go dry?, *Water Resour. Res.*, *44*, W03201, doi:10.1029/2007WR006704.

Barnett, T. P., and D. W. Pierce (2009), Sustainable water deliveries from the Colorado River in a changing climate, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(18), 7334–7338.

Belmecheri, S., F. Babst, E. R. Wahl, D. W. Stahle, and V. Trouet (2016), Multi-century evaluation of Sierra Nevada snowpack, *Nat. Clim. Change.*, 2–3.

Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo (1996), The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, *J. Geophys. Res.*, *101*(D3), 7209–7225.

Brekke, L., B. Harding, T. Piechota, B. Udall, C. Woodhouse, and D. Yates (2007), *Review of Science and Methods for Incorporating Climate Change Information into Reclamation's Colorado River Basin Planning Studies*, Reclamation, Washington, D. C.

Brekke, L., B. Thrasher, Maurer, Edwin P., and T. Pruitt (2013), *Downscaled CMIP3 and CMIP5 Climate Projections*, Reclamation, Washington, D.C.

Brekke, L., A. Wood, and T. Pruitt (2014), *Downscaled CMIP3 and CMIP5 Hydrology Projections*, Reclamation, Washington, D. C.

Breshears, D. D., et al. (2005), Regional vegetation die-off in response to global-change-type drought, *Proc. Natl. Acad. Sci. U. S. A.*, *102*(42), 15,144–15,148.

Brubaker, K. L., and D. Entekhabi (1996), Analysis of feedback mechanisms in land-atmosphere interaction, *Water Resour. Res.*, *32*(5), 1343–1357.

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov (2010), Future dryness in the southwest US and the hydrology of the early 21st century drought, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(50), 21,271–21,276, doi:10.1073/pnas.0912391107.

Central Arizona Project (2016), *Lower Basin Drought Contingency Plan*, Central Arizona Project, Phoenix, AZ.

Christensen, N. S., and D. P. Lettenmaier (2007), A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin, *Hydrol. Earth Syst. Sci. Discuss.*, *11*(4), 1417–1434.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River basin, *Clim. Change*, *62*(1–3), 337–363.

Collins, M., et al. (2013), Long-term climate change: Projections, commitments and irreversibility, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., Cambridge Univ. Press, Cambridge, U. K.

Collum, C., and T. McCann (2014), *Central Arizona Project Board Report Agenda Number 9*, Central Arizona Project, Phoenix, AZ.

Colorado River Basin Stakeholders (2015), *Colorado River Basin Stakeholders Moving Forward to Address Challenges Identified in the Colorado River Basin Water Supply and Demand Study, Phase 1 Report*, Bureau of Reclamation, Washington, D. C.

Cook, B. I., J. E. Smerdon, R. Seager, and S. Coats (2014), Global warming and 21st century drying, *Clim. Dyn.*, *43*(9–10), 2607–2627.

Cook, B. I., T. R. Ault, and J. E. Smerdon (2015), Unprecedented 21st century drought risk in the American Southwest and Central Plains, *Sci. Adv.*, *1*(1), e1400082, doi:10.1126/sciadv.1400082.

Dai, A. (2012), Increasing drought under global warming in observations and models, *Nat. Clim. Change*, *3*(1), 52–58, doi:10.1038/nclimate1633.

Daly, C., R. P. Neilson, and D. L. Phillips (1994), A statistical-topographic model for mapping climatological precipitation over mountainous terrain, *J. Appl. Meteorol.*, *33*(2), 140–158.

Das, T., D. W. Pierce, D. R. Cayan, J. A. Vano, and D. P. Lettenmaier (2011), The importance of warm season warming to western U.S. streamflow changes, *Geophys. Res. Lett.*, *38*, L23403, doi:10.1029/2011GL049660.

Davis, T. (2016), Big CAP cuts coming as 3-state water agreement nears, *Ariz. Dly. Star.* [Available at http://tucson.com/news/local/big-cap-cuts-coming-as–state-water-agreement-nears/article_876e3aa6-6cf0-53ec-bd0c-95be8c6468ae.html.]

Deems, J. S., T. H. Painter, J. J. Barsugli, J. Belnap, and B. Udall (2013), Combined impacts of current and future dust deposition and regional warming on Colorado River Basin snow dynamics and hydrology, *Hydrol. Earth Syst. Sci.*, *17*(11), 4401–4413, doi:10.5194/hess-17-4401-2013.

Department of Interior (2007), *Record of Decision Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead*, Dep. of Inter., Washington, D. C.

Diffenbaugh, N. S., D. L. Swain, and D. Touma (2015), Anthropogenic warming has increased drought risk in California, *Proc. Natl. Acad. Sci. U. S. A.*, *112*(13), 3931–3936, doi:10.1073/pnas.1422385112.

Elias, E. H., A. Rango, C. M. Steele, J. F. Mejia, and R. Smith (2015), Assessing climate change impacts on water availability of snowmelt-dominated basins of the Upper Rio Grande basin, *J. Hydrol. Reg. Stud.*, *3*, 525–546, doi:10.1016/j.ejrh.2015.04.004.

Feng, S., and Q. Fu (2013), Expansion of global drylands under a warming climate, *Atmos. Chem. Phys.*, *13*(19), 10,081–10,094, doi:10.5194/acp-13-10081-2013.

Ficklin, D. L., I. T. Stewart, and E. P. Maurer (2013), Climate change impacts on streamflow and subbasin-scale hydrology in the Upper Colorado River Basin, edited by V. Shah, *PLoS One*, *8*(8), e71297, doi:10.1371/journal.pone.0071297.

Glennon, R. J. (1995), Coattails of the past: Using and financing the Central Arizona Project, *Ariz. State Law J.*, *27*, 677–756.

Griffin, D., and K. J. Anchukaitis (2014), How unusual is the 2012–2014 California drought?, *Geophys. Res. Lett.*, *41*, 9017–9023, doi:10.1002/2014GL062433.

AGU Water Resources Research 10.1002/2016WR019638

Guentchev, G., J. J. Barsugli, and J. Eischeid (2010), Homogeneity of gridded precipitation datasets for the Colorado River Basin, *J. Appl. Meteorol. Climatol.*, *49*(12), 2404–2415, doi:10.1175/2010JAMC2484.1.

Harding, B. L., A. W. Wood, and J. R. Prairie (2012), The implications of climate change scenario selection for future streamflow projection in the Upper Colorado River Basin, *Hydrol. Earth Syst. Sci.*, *16*(11), 3989–4007, doi:10.5194/hess-16-3989-2012.

James, I. (2016), Lake Mead declines to lowest level in history, *Desert Sun.* [Available at http://www.desertsun.com/story/news/environment/2016/05/19/lake-mead-declines-new-record-low/84597120/.]

Johnson, R. (1977), *The Central Arizona Project, 1918–1968*, Univ. of Arizona Press, Tucson, Ariz.

Koirala, S., Y. Hirabayashi, R. Mahendran, and S. Kanae (2014), Global assessment of agreement among streamflow projections using CMIP5 model outputs, *Environ. Res. Lett.*, *9*(6), 64,017, doi:10.1088/1748-9326/9/6/064017.

Liang, X., D. P. Lettenmaier, and E. F. Wood (1996), One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model, *J. Geophys. Res.*, *101*(D16), 21,403–21,422.

Lukas, J., J. Barsugli, N. Doesken, I. Rangwala, and K. Wolter (2014), *Climate Change in Colorado A Synthesis to Support Water Resources Management and Adaptation*, Western Water Assessment, Boulder, CO.

Mann, M. E., and P. H. Gleick (2015), Climate change and California drought in the 21st century, *Proc. Natl. Acad. Sci. U. S. A.*, *112*(13), 3858–3859, doi:10.1073/pnas.1503667112.

Mann, M. E., Z. Zhang, S. Rutherford, R. S. Bradley, M. K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni (2009), Global signatures and dynamical origins of the little ice age and medieval climate anomaly, *Science*, *326*(5957), 1256–1260, doi:10.1126/science.1177303.

McCabe, G. J., and D. M. Wolock (2007), Warming may create substantial water supply shortages in the Colorado River basin, *Geophys. Res. Lett.*, *34*, L22708, doi:10.1029/2007GL031764.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell (2007), THE WCRP CMIP3 multimodel dataset: A new era in climate change research, *Bull. Am. Meteorol. Soc.*, *88*(9), 1383–1394, doi:10.1175/BAMS-88-9-1383.

Meko, D. M., C. A. Woodhouse, C. A. Baisan, T. Knight, J. J. Lukas, M. K. Hughes, and M. W. Salzer (2007), Medieval drought in the upper Colorado River Basin, *Geophys. Res. Lett.*, *34*, L10705, doi:10.1029/2007GL029988.

Milly, P. C. D., and K. A. Dunne (2016), Potential evapotranspiration and continental drying, *Nat. Clim. Change*, *6*(10), 946–949, doi:10.1038/nclimate3046.

Milly, P. C. D., K. A. Dunne, and A. V. Vecchia (2005), Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, *438*(7066), 347–350, doi:10.1038/nature04312.

Moss, R. H., et al. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, *463*(7282), 747–756.

Nash, L. L., and P. H. Gleick (1991), Sensitivity of streamflow in the Colorado basin to climatic changes, *J. Hydrol.*, *125*(3), 221–241.

National Research Council (2007), *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*, The Natl. Acad. Press, Washington, D. C.

Norris, J. R., R. J. Allen, A. T. Evan, M. D. Zelinka, C. W. O'Dell, and S. A. Klein (2016), Evidence for climate change in the satellite cloud record, *Nature*, *536*(7614), 72–75, doi:10.1038/nature18273.

Nowak, K., M. Hoerling, B. Rajagopalan, and E. Zagona (2012), Colorado River Basin hydroclimatic variability, *J. Clim.*, *25*(12), 4389–4403, doi:10.1175/JCLI-D-11-00406.1.

Overpeck, J. T. (2013), Climate science: The challenge of hot drought, *Nature*, *503*(7476), 350–351.

Oyler, J. W., S. Z. Dobrowski, A. P. Ballantyne, A. E. Klene, and S. W. Running (2015a), Artificial amplification of warming trends across the mountains of the western United States, *Geophys. Res. Lett.*, *42*, 153–161, doi:10.1002/2014GL062803.

Oyler, J. W., A. Ballantyne, K. Jencso, M. Sweet, and S. W. Running (2015b), Creating a topoclimatic daily air temperature dataset for the conterminous United States using homogenized station data and remotely sensed land skin temperature, *Int. J. Climatol.*, *35*(9), 2258–2279, doi:10.1002/joc.4127.

Painter, T. H., J. S. Deems, J. Belnap, A. F. Hamlet, C. C. Landry, and B. Udall (2010), Response of Colorado River runoff to dust radiative forcing in snow, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(40), 17,125–17,130.

Pitman, A. J. (2003), The evolution of, and revolution in, land surface schemes designed for climate models, *Int. J. Climatol.*, *23*(5), 479–510, doi:10.1002/joc.893.

Prein, A. F., G. J. Holland, R. M. Rasmussen, M. P. Clark, and M. R. Tye (2016), Running dry: The U.S. Southwest's drift into a drier climate state, *Geophys. Res. Lett.*, *43*, 1272–1279, doi:10.1002/2015GL066727.

Rajagopalan, B., K. Nowak, J. Prairie, M. Hoerling, B. Harding, J. Barsugli, A. Ray, and B. Udall (2009), Water supply risk on the Colorado River: Can management mitigate? *Water Resour. Res.*, *45*, W08201, doi:10.1029/2008WR007652.

Rangwala, I., T. Bardsley, M. Pescinski, and J. Miller (2015), *SNOTEL Sensor Upgrade has Caused Temperature Record Inhomogeneities for the Intermountain West: Implications for Climate Change Impact Assessments*, West. Water Assess., Boulder, Colo.

Ray, A. J., J. J. Barsugli, K. B. Averyt, K. Wolter, M. Hoerling, N. Doesken, B. Udall, and R. S. Webb (2008), *Climate change in Colorado: a synthesis to support water resources management and adaptation*, Western Water Assessment, Boulder, Colo.

Reclamation (2007), *Final Environmental Impact Statement Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*, Bureau of Reclamation, Boulder City, NV.

Reclamation (2012), *Colorado River Basin Water Supply and Demand Study*, U.S. Dep. of the Inter., Bur. of Reclam., Tech. Serv. Cent., Denver, Colo.

Reclamation (2013), *West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment*, U.S. Department of the Interior, Bureau of Reclamation, Albuquerque, NM.

Reclamation (2016), *SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water*., U.S. Department of the Interior, Bureau of Reclamation, Denver, Colo.

Salzer, M. W., and K. F. Kipfmueller (2005), Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau, USA, *Clim. Change*, *70*(3), 465–487.

Salzer, M. W., A. G. Bunn, N. E. Graham, and M. K. Hughes (2014), Five millennia of paleotemperature from tree-rings in the Great Basin, USA, *Clim. Dyn.*, *42*(5–6), 1517–1526.

Scheff, J., and D. M. Frierson (2012), Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones, *Geophys. Res. Lett.*, *39*, L18704, doi:10.1029/2012GL052910.

Seager, R., et al. (2007), Model projections of an imminent transition to a more arid climate in Southwestern North America, *Science*, *316*(5828), 1181–1184, doi:10.1126/science.1139601.

Seager, R., M. Ting, C. Li, N. Naik, B. Cook, J. Nakamura, and H. Liu (2012), Projections of declining surface-water availability for the southwestern United States, *Nat. Clim. Change*, *3*(5), 482–486, doi:10.1038/nclimate1787.

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson (2015a), Causes of the 2011–14 California Drought*, *J. Clim.*, *28*(18), 6997–7024.

AGU Water Resources Research 10.1002/2016WR019638

Seager, R., A. Hooks, A. P. Williams, B. Cook, J. Nakamura, and N. Henderson (2015b), Climatology, variability, and trends in the US vapor pressure deficit, an important fire-related meteorological quantity*, *J. Appl. Meteorol. Climatol.*, *54*(6), 1121–1141.

Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling (2010), Investigating soil moisture-climate interactions in a changing climate: A review, *Earth Sci. Rev.*, *99*(3), 125–161.

Solomon, S., G.-K. Plattner, R. Knutti, and P. Friedlingstein (2009), Irreversible climate change due to carbon dioxide emissions, *Proc. Natl. Acad. Sci. U. S. A.*, *106*(6), 1704–1709, doi:10.1073/pnas.0812721106.

Swann, A. L. S., F. M. Hoffman, C. D. Koven, and J. T. Randerson (2016), Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity, *Proc. Natl. Acad. Sci. U. S. A.*, *113*, 10,019–10,024, doi:10.1073/pnas.1604581113.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl (2012), An overview of Cmip5 and the experiment design, *Bull. Am. Meteorol. Soc.*, *93*(4), 485–498.

Tipton and Kalmbach, Inc. (1965), *Water Supplies of the Colorado River*, Upper Colo. River Comm., Denver, Colo.

Udall, J. (1983), Floods reveal water policy chaos, *High Ctry. News*, *15*(18), 1–10.

Ukkola, A. M., I. C. Prentice, T. F. Keenan, A. I. J. M. van Dijk, N. R. Viney, R. B. Myneni, and J. Bi (2015), Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation, *Nat. Clim. Change*, *6*(1), 75–78, doi:10.1038/nclimate2831.

Vano, J. A., and D. P. Lettenmaier (2014), A sensitivity-based approach to evaluating future changes in Colorado River discharge, *Clim. Change*, *122*(4), 621–634, doi:10.1007/s10584-013-1023-x.

Vano, J. A., T. Das, and D. P. Lettenmaier (2012), Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature*, *J. Hydrometeorol.*, *13*(3), 932–949, doi:10.1175/JHM-D-11-069.1.

Vano, J. A., et al. (2014), Understanding uncertainties in future Colorado River streamflow, *Bull. Am. Meteorol. Soc.*, *95*(1), 59–78.

Verburg, K. O. (2011), *Colorado River Documents 2008*, Reclamation, Denver, Colo.

Weiss, J. L., C. L. Castro, and J. T. Overpeck (2009), Distinguishing pronounced droughts in the Southwestern United States: Seasonality and effects of warmer temperatures, *J. Clim.*, *22*(22), 5918–5932, doi:10.1175/2009JCLI2905.1.

Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook (2015), Contribution of anthropogenic warming to California drought during 2012–2014, *Geophys. Res. Lett.*, *42*, 6819–6828, doi:10.1002/2015GL064924.

Wines, M. (2014), Colorado River drought forces a painful reckoning for states, *New York Times*, 6th January.

Woodhouse, C. A., S. T. Gray, and D. M. Meko (2006), Updated streamflow reconstructions for the Upper Colorado River basin, *Water Resour. Res.*, *42*, W05415, doi:10.1029/2005WR004455.

Woodhouse, C. A., G. T. Pederson, K. Morino, S. A. McAfee, and G. J. McCabe (2016), Increasing influence of air temperature on upper Colorado River streamflow, *Geophys. Res. Lett.*, *43*, 2174–2181, doi:10.1002/2015GL067613.

On the Causes of Declining Colorado River Streamflows

Article *in* Water Resources Research · August 2018

DOI: 10.1029/2018WR023153

Mu Xiao
University of California, Los Angeles

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2018WR023153

Key Points:

- The naturalized flow of the Colorado River has decreased about 15% over the last 100 years
- About half of the long-term trend is attributable to rising temperatures with the remainder due to changes in precipitation patterns and other factors
- Slightly over half of the flow reduction during the post-2000 Millennium Drought is attributable to anomalously warm temperatures

Supporting Information:

- Figure S1

Correspondence to:
D. P. Lettenmaier,
dlettenm@ucla.edu

Citation:
Xiao, M., Udall, B., & Lettenmaier, D. P. (2018). On the causes of declining Colorado River streamflows. *Water Resources Research*, *54*. https://doi.org/10.1029/2018WR023153

Received 17 APR 2018
Accepted 22 AUG 2018
Accepted article online 30 AUG 2018

On the Causes of Declining Colorado River Streamflows

Mu Xiao[1], Bradley Udall[2], and Dennis P. Lettenmaier[1]

[1]Department of Geography, University of California, Los Angeles, CA, USA, [2]Colorado Water Institute, Colorado State University, Fort Collins, CO, USA

Abstract The Colorado River is the primary surface water resource in the rapidly growing U.S. Southwest. Over the period 1916–2014, the Upper Colorado River Basin naturalized streamflow declined by 16.5%, despite the fact that annual precipitation in the UCRB over that period increased slightly (+1.4%). In order to examine the causes of the runoff declines, we performed a set of experiments with the Variable Infiltration Capacity hydrology model. Our results show that the pervasive warming has reduced snowpacks and enhanced evapotranspiration over the last 100 years; over half (53%) of the long-term decreasing runoff trend is associated with the general warming. Negative winter precipitation trends have occurred in the handful of highly productive subbasins that account for over half of the streamflow at Lee's Ferry. We also compared a midcentury drought with the (ongoing) post-Millennium Drought and find that whereas the earlier drought was caused primarily by pervasive low-precipitation anomalies across UCRB, higher temperatures have played a large role in the post-Millennium Drought. The post-Millennium Drought has also been exacerbated by negative precipitation anomalies in several of the most productive headwater basins. Finally, we evaluate the UCRB April–July runoff forecast for 2017, which decreased dramatically as the runoff season progressed. We find that while late winter and spring 2017 was anomalously warm, the proximate cause of most of the forecast reduction was anomalous late winter and early spring dryness in UCRB, which followed exceptionally large (positive) early winter precipitation anomalies.

Plain Language Summary As the essential water resource for the Southwest United States, the Upper Colorado River Basin (UCRB) unimpaired streamflow declined by 16.5% over 1916–2014, while annual precipitation increased slightly (+1.4%). We performed a set of experiments with a hydrology model that uses temperature and precipitation as inputs to diagnose the causes of this apparent anomaly. We find that over half (53%) of the decreasing runoff trend is associated with unprecedented basin-wide warming, which has reduced snowpack and increased plant water use. The remaining ~47% of the trend is associated mostly with reduced winter precipitation in four highly productive subbasins, all located in Colorado. We compared the 1953–1967 drought with the 2000–2014 Millennium Drought and find that the earlier drought was caused primarily by precipitation declines across the entire UCRB but higher temperatures caused about half of the 2000–2014 flow loss. The Millennium Drought was also caused by precipitation reductions in the four most productive subbasins. We evaluated the UCRB April–July runoff forecast for 2017, which decreased dramatically as the runoff season progressed. The late winter and spring 2017 was anomalously warm, but most of the reduction was due to late season dryness.

1. Introduction

The Colorado River is the largest river in the southwestern U.S. It is the source of drinking water for many of the Colorado River Basin's 40 million people and provides irrigation water to ~13,000 km^2 of crops in the U.S. and Mexico (Cohen et al., 2013). It is a lifeline for the population and agricultural economy of parts of seven U.S. states (WY, UT, CO, NV, NM, AZ, and CA) and the Mexican states of Sonora and Baja California. The river's naturalized streamflow (see section 2.2 for discussion of naturalized streamflows) at Imperial Dam (the downstreammost long-term gauging station) has averaged about 20.7 km^3/yr (16.8 maf/yr) over the last century, approximately 90% of which is generated in the Upper Colorado River Basin (McCabe & Wolock, 2007), defined as the~289,000 km^2 of drainage area upstream of the U.S. Geological Survey stream gauge at Lees Ferry, AZ (USGS 09380000). Snowpack stored in the high-elevation Rocky Mountain headwater basins contributes about 70% of the annual streamflow (Christensen et al., 2004).

The Colorado River is heavily regulated, mostly by Glen Canyon Dam (Lake Powell) and Hoover Dam (Lake Mead), with combined reservoir storage capacity of 67.5 km^2 (54.7 maf). The importance of these

Water Resources Research 10.1029/2018WR023153

reservoirs, which can store close to 4 times the natural annual flow at Lees Ferry, AZ, has become especially evident during the so-called Millennium Drought, which began about 2000. This drought has coincided with increases in water demand (Rajagopalan et al., 2009), which resulted in Lake Mead reaching its lowest level on record in October 2016. Lakes Mead and Powell dropped precipitously from 2000 to 2004 due to very low flows (71%, 74%, 41%, 71%, and 64% of average, respectively) and have not recovered due to continued high demands equal to inflows and a lack of high flow years. Indeed, only four of the last 18 years have had above average river discharge, limiting reservoir refill opportunities.

A pronounced warming trend across the Colorado River Basin (CRB) since the 1970s (Dawadi & Ahmad, 2012) has further contributed to the post-2000 imbalance between CRB runoff and water demand. Vano et al. (2012) evaluated the temperature sensitivity (annual average streamflow change per 1 °C temperature change) and found that the average sensitivity of annual runoff at Lees Ferry was around −5%/°C), suggesting that warming over the last ~50 years may account for a 5–10% reduction in annual streamflow over that period.

Several studies have investigated the effects of ongoing warming on the flow of the Colorado River. Barnett and Pierce (2009) concluded that anthropogenic climate change would reduce CRB runoff by 10%–30% by 2050. Reynolds et al. (2015) predicted that minimum streamflows will decline as warming of the basin continues. Woodhouse et al. (2016) reported an increase in the frequency of warm years with low streamflow since 1988. McCabe et al. (2017) found that increases in temperature since the late 1980s have decreased runoff generation efficiency, reducing streamflows by 7%. Udall and Overpeck (2017) similarly found temperature-induced streamflow decreases of approximately 6% during 2000–2014 and projected large midcentury temperature-induced declines of 20% or more should precipitation not change.

Here we utilize a hydrological model applied for the period 1916–2014 (all data are for water years if not specified otherwise) to evaluate the spatial and temporal signature of the Millennium Drought in the CRB. Along with a baseline simulation forced by gridded observations, we perform a T-detrend experiment, in which we remove the long-term temperature trend from the model forcings, to investigate the role of the warming on streamflow declines both over the long term and during the recent drought. We analyze runoff in each of 20 subbasins of the CRB, which allows us to study spatial variations in runoff generation and anomalies. We also analyze the historical 1953–1968 drought in an attempt to shed light on how the hydrologic response to climate variations has changed in recent decades and during the Millennium Drought in particular. Finally, we dissect the 2017 April–July streamflow forecast to understand the role of late winter and early spring precipitation and temperature in the substantial seasonal forecast reductions that occurred as water year 2017 progressed.

2. Data and Approach

2.1. VIC Model and Forcings

The Variable Infiltration Capacity (VIC) model is a physically based, semidistributed hydrological model, which represents the land surface water and energy budgets over a grid mesh (here 1/16th degree spatial resolution) and routes runoff through a prescribed river network to produce streamflow estimates at specified river nodes (Liang &Lettenmaier, 1994). We applied the model at a daily time step, using what is termed full-energy balance mode, meaning that the model iteratively solves the surface energy budget by estimating the effective surface temperature at each time step. Therefore, the daily average surface temperature produced by VIC is not the average of the forcing temperatures, that is, 0.5*(daily maximum + daily minimum). Unless stated otherwise, the temperatures we report here are outputs from the VIC simulations.

Similar to other land surface models, the fundamental water balance equation in VIC can be summarized as Runoff (RO) = Precipitation (P) − Evapotranspiration (ET) − changes in Soil Moisture (ΔSM) − changes in Snow Water Equivalent (ΔSWE). Groundwater is not represented in the version of VIC we used; Rosenberg et al. (2013) found that inclusion of a parameterization of groundwater had little effect on the model's streamflow simulations in the CRB. It is important to note that VIC represents snowpack sublimation within its winter ET. Sublimation is sparsely measured but nonetheless is important to some aspects of our study (Andreadis et al., 2009); we describe the model's performance with respect to sublimation in section 4.2.

Water Resources Research
10.1029/2018WR023153

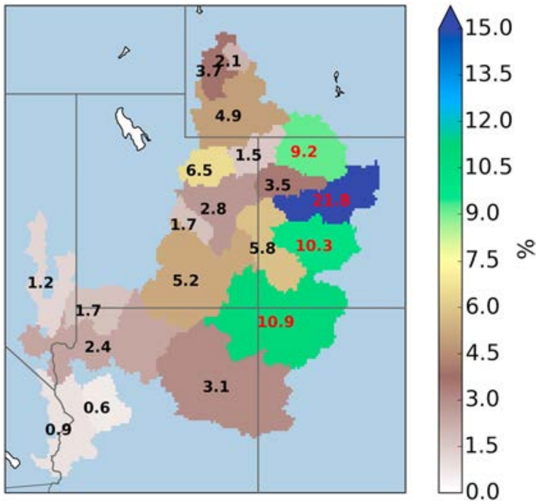


Figure 1. Percent of total CRB runoff (at Imperial Dam) originating from 20 subbasins, calculated based on long-term average from VIC simulation for water years 1971–2014. The subbasins shown in Figure 1 were extracted from a published data set by Wu et al. (2012).

The VIC model has been successfully applied previously in a number of hydrological studies over the CRB and the U.S. Southwest (Christensen et al., 2004; Christensen & Lettenmaier, 2007; Mote et al., 2005, 2018; Vano et al., 2012, 2014).

The VIC model simulates surface hydrological processes with parameterizations of subgrid vegetation, soil variability, and topography and has provided plausible representations of CRB surface water conditions in the above-referenced studies. We forced the model with an updated version of the Hamlet and Lettenmaier (hereafter H&L) data set (Hamlet & Lettenmaier, 2005) at 1/16° resolution for the period water years 1916–2014. We chose the H&L data set because its long-term variability is indexed to the U.S. Historical Climatology Network (HCN; Easterling et al., 1996) stations in the region, which have been carefully quality controlled for effects that could otherwise result in spurious trends, such as station moves and instrument changes (e.g., the shift to maximum-minimum temperature system temperature sensors in the 1980s). As described in Hamlet and Lettenmaier (2005), the H&L data set uses HCN station data to constrain decadal variability (and hence long-term trends), hence is in our view most appropriate for exploration of the causes of century-scale streamflow declines over our study period 1916–2014.

2.2. Naturalized Streamflows

To evaluate our model simulation results, we used naturalized streamflow data for the Colorado River produced by the U.S. Bureau of Reclamation (USBR); see https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html for details. The naturalized streamflows are derived from USGS historical streamflow observations by a process of adjustments that compensate for anthropogenic effects including consumptive uses of water, reservoir storage, transbasin diversions, and other effects (see USBR, 1983). The naturalized streamflow data sets are produced for 29 well-distributed tributary stations across the CRB (as well as the main stem) for the period 1906 through 2015. Others (Prairie & Callejo, 2005) have noted that USBR has improved the quality of the naturalized flow data set after 1971 and the estimates may be somewhat better after that time.

2.3. Subbasin Analysis

We performed our analyses for the Colorado River above Imperial Dam, as well as for the 20 subbasins delimited by USGS WaterWatchgauges (see Figure 1), which are a subset of the 29 naturalized streamflow points noted above. The river channel network data set we used is from Wu et al. (2012), based on which we determined the masks for each of the 20 subbasins. The Wu et al. subbasins are similar to, but slightly different from, the more familiar six-digit Hydrologic Unit Codes normally used in the basin. Detailed information about each subbasin is reported in the supporting information.

It is important to note that our analysis excludes the Gila River given its distinct hydrological and legal characteristics. The Gila River joins the Colorado River below Imperial Dam just upstream of the U.S. border with Mexico and in recent years has been mostly dry at its mouth due to upstream uses by Arizona. Since 1964, the U.S. Supreme Court has excluded it from administration under the Colorado River Compact. Although the Gila is an important basin, its absence from this study is logical given its unique status.

Table 1
Naturalized (NFL) and VIC Runoff Contribution Percentages for Selected USGS Gauges

Station name	NFL	VIC
COLORADO RIVER NEAR CAMEO (09095500)	22.8%	21.8%
GUNNISON RIVER NEAR GRAND JUNCTION (09152500)	14.6%	10.3%
SAN JUAN RIVER NEAR BLUFF (09379500)	12.4%	10.9%
GREEN RIVER NEAR GREENDALE (09234500)	12.2%	10.7%
WHITE RIVER NEAR WATSON (09306500)	3.5%	3.5%
DUCHESNE RIVER NEAR RANDLETT (09302000)	4.8%	6.5%
YAMPA RIVER AT DEERLODGE PARK (09260050)	8.0%	9.2%
COLORADO RIVER AT LEES FERRY LEEFY (09380000)	91.8%	91.0%
COLORADO RIVER ABOVE IMPERIAL DAM (09429490)	100%	100%

Note. Values are computed relative to the annual streamflow climatology at the Imperial Dam, AZ-CA. The percentages are relative to long-term averages for water year 1971–2014.

2.4. Model Testing and Evaluation

Table 1 summarizes the long-term runoff contribution percentages from nine major subbasins at which naturalized streamflows are available and for which we also produced VIC simulations. The runoff contribution percentages from the model and naturalized flows generally are in good agreement. The Upper Basin (UCRB; defined as the drainage area above

Water Resources Research 10.1029/2018WR023153

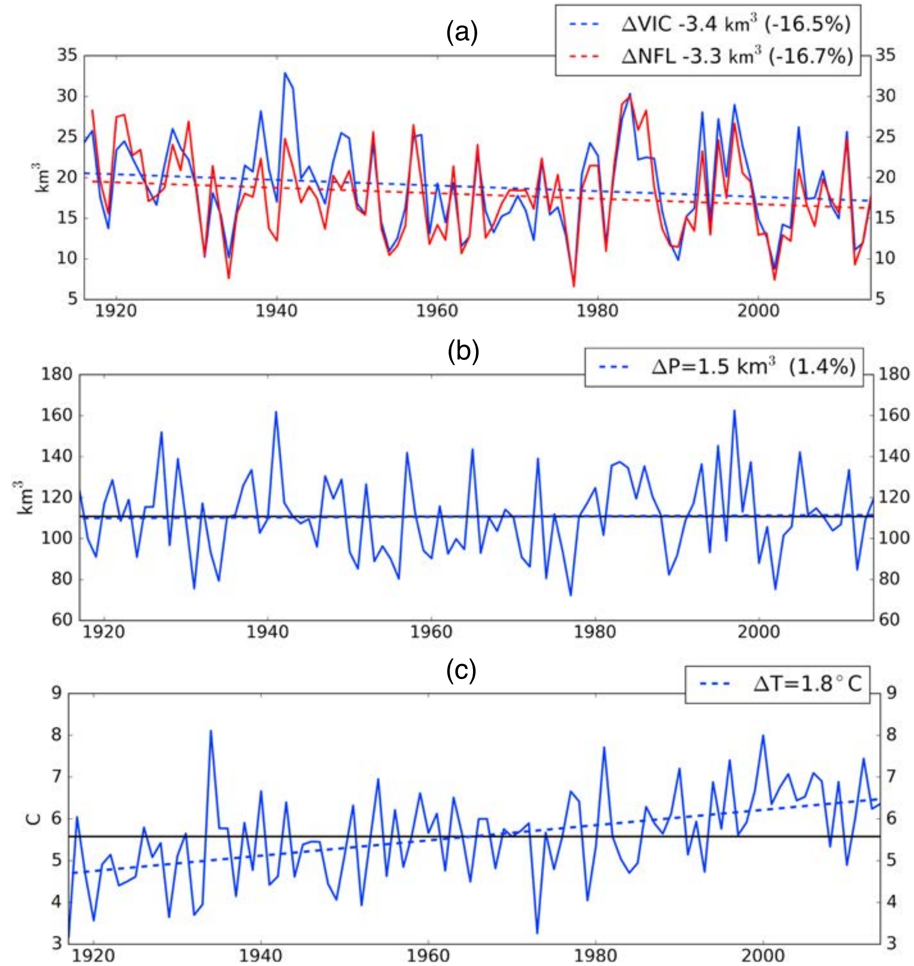


Figure 2. Annual time series and linear regression trend plots for Colorado River Basin above Lees Ferry: (a) annual (naturalized) runoff, (b) annual precipitation, and (c) annual average surface temperature calculated by VIC. Changes are calculated relative to the starting value of the fit. Note that precipitation (b) is from an extended version of the Hamlet and Lettenmaier (2005) data set at 1/16th degree spatial resolution, while temperature (c) is calculated from VIC and is approximately 0.4 °C warmer than the Hamlet and Lettenmaier input temperature.

Lees Ferry, AZ) produces more than 90% of the flow at Imperial Dam. Therefore, we mainly focus on the UCRB here, acknowledging unusual Lower Basin (LCRB) conditions when noteworthy.

Figure 2a shows the annual time series of naturalized streamflow (NFL) and VIC simulations at Lees Ferry, AZ. Both the annual naturalized streamflows and VIC simulations (r^2 = 0.75) and their trends over the period of record (NFL: −3.3 km^3/yr, VIC: −3.4 km^3/yr) are similar, suggesting that the VIC model provides a plausible representation of natural conditions (i.e., those responding primarily to climate forcings) and long-term hydrologic change in the basin. Hereafter, we mainly focus on VIC results in our analysis of UCRB subbasin long-term (1916–2014) trends and comparison between the 1953–1968 and the Millennium drought. The annual precipitation and average temperature (calculated by VIC as noted in section 2.1) time series plots are also presented in Figure 2.

3. Results

3.1. Basin-Wide Trend Analysis

Table 2 summarizes long-term linear (regression) trends for the UCRB for four hydrological variables (precipitation, evapotranspiration, runoff, and 1 April snow water equivalent) from the baseline VIC simulation and the temperature-detrended (T-detrend) simulation. We also computed trends using the

Water Resources Research 10.1029/2018WR023153

Table 2
UCRB Annual and Seasonal Changes in Water Balance Variables Over Water Years 1916–2014 in km^3/yr (km^3 for SWE) and Percentages Relative to the Starting Value of the Fit

	P	T	ET	ET-D	RO	RO-D	SWE	SWE-D
Annual	1.5 (1.4%)	1.8	4.2 (4.7%)	2.3 (2.6%)	−3.4 (−16.5%)	−1.6 (−7.7%)	−9.1 (−39.0%)	−5.6 (−23.9%)
Winter	−0.1 (−0.2%)	1.9	4.9 (30.5%)	2.9 (18.0%)	0.4 (10.4%)	0.4 (9.0%)	Na	Na
Summer	1.6 (3.0%)	1.7	−0.8 (−1.1%)	−0.6 (−0.8%)	−3.8 (−23.3%)	−1.9 (−11.9%)	Na	Na

Note. P is precipitation, T is temperature in Celsius, ET is evapotranspiration, RO is total runoff, and SWE is 1 April snow water equivalent. Dashed "D" denotes results from T-detrend simulation. Winter period is October–March, and summer period is April–September.

nonparametric Theil-Sen slope estimator (Sen, 1968; Theil, 1950) and found that they generally are in close agreement (Table S1). Therefore, we refer to the linear trends hereafter for convenience. The T-detrend simulation uses the same forcings as the baseline, except that annual linear trends in the daily temperature maxima and minima are removed. We also disaggregated summer season (April–September) and winter season (October–March) for each variable (all summers and winters mentioned hereafter are so defined).

Over the simulation period 1916–2014 the UCRB annual precipitation increased by +1.5 km^3 (1.4%), whereas winter precipitation, which is the main source for 1st April snow water equivalent and streamflow in the spring and summer, had only a very small (not statistically significant) negative trend (long-term ΔP is −0.1 km^3, −0.2%). In our baseline simulation, the long-term linear change of annual runoff (ΔRO) in the UCRB is −3.4 km^3 (−16.5%) and long-term change in annual evapotranspiration (ΔET) is +4.2 km^3 (+4.7%). The 1st April SWE decreased significantly (ΔSWE −9.1 km^3, −39.0%), which reduces warm season streamflow from the Upper Basin, as evidenced by summer RO decreases (−3.8 km^3, −23.3%) even given a positive trend in summer precipitation (ΔP_{summer} is +1.6 km^3). As summer RO makes up more than 3/4 of the annual RO in the UCRB, the long-term annual ΔRO is negative as noted above, although summer RO decreases are slightly compensated by increasing winter RO (ΔRO_{winter} + 0.4 km^3, 10.4%).

We performed the T-detrend simulation using the same precipitation as the baseline simulation but with the temperature trend removed from the forcing data set on a grid cell by grid cell basis. In this no-warming-trend scenario, the long-term decreasing trend in annual runoff is reduced to −1.6 km^3(−7.7%), from −3.4 km^3 but not eliminated. It suggests that 53% (−1.8/ −3.4) of the annual runoff trend is attributable to the annual warming temperature. The increase in ET in the T-detrend simulation is smaller by 1.9 km^3 (baseline: +4.2 km^3, T-detrend: +2.3 km^3), which explains the increase in runoff (1.8 km^3) to within 0.1 km^3.

The numbers in Table 2 also show that the effects of the temperature trend on winter RO (baseline: +0.4 km^3, T-detrend: +0.4 km^3) and summer ET (baseline: −0.8 km^3, T-detrend: −0.6 km^3) are small. Increasing temperatures cause a decrease in summer RO (baseline: −3.8 km^3, T-detrend: −1.9 km^3) and an increase in annual ET (baseline: +4.2 km^3, T-detrend: +2.3 km^3) that comes mostly in the winter (baseline: +4.9 km^3, T-detrend: +2.9 km^3). On a percentage basis, both of these increasing winter trends in ET are substantial over the 1906–2014 period: a 30% increase in the baseline ET and an 18% increase in the T-detrend simulation ET. The summer ET changes of −1.1% and −0.8% are comparatively small. It is worth noting that the long-term trend in UCRB winter ET is positive in the T-detrend simulation even given no significant trend in winter precipitation. The positive trend in winter ET is mainly caused by increased snow sublimation. Although sublimation is strongly controlled by surface temperature, other factors also contribute as well (see section 4).

The remaining −1.6 km^3 (−7.7%) decrease in RO in the T-detrend simulation is curious given the increasing summer precipitation (ΔP_{summer} + 1.6 km^3, 3.0%) and negligible winter precipitation change (ΔP_{winter} − 0.1 km^3, −0.2%). In addition, although the SWE anomaly in the T-detrend simulation is less compared with that of the baseline simulation (baseline: −9.1 km^3, T-detrend: −5.6 km^3), the long-term 1906–2014 SWE trend is still negative in the T-detrend simulation (−23.9%). Winter ΔET in the T-detrend simulation is only +2.9 km^3 as reported in Table 2, which cannot explain all of the SWE anomaly. One possible answer is that while the overall basin-wide precipitation changes over time are small, precipitation declines in the most productive basins while increasing in the less productive basins. We explore the effects of such spatial variations below.

Water Resources Research
10.1029/2018WR023153

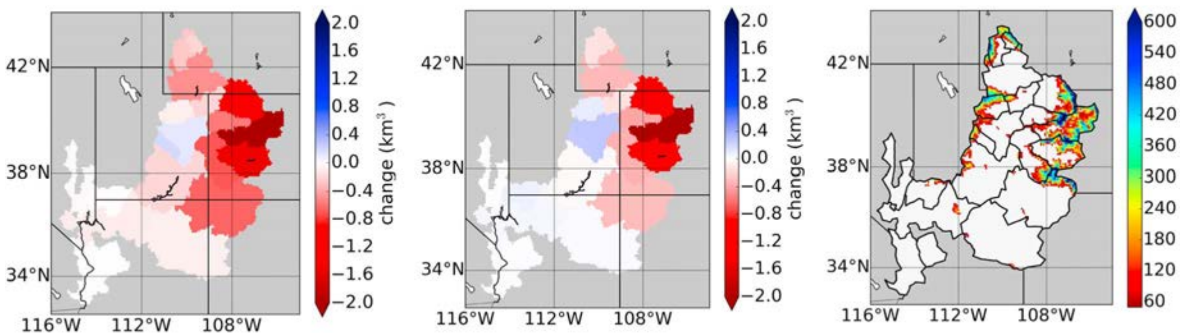


Figure 3. Spatial plots of 1 April SWE trends for (a) baseline simulation and (b) T-detrend simulation over each subbasin. The changes over 1916–2014 are calculated relative to starting value of the linear regressions. (c) Long-term average 1 April SWE.

3.2. Subbasin Conditions

Figure 1 shows that there are four subbasins in the upper CRB (denoted by red numbers) that produce most of the UCRB runoff: the Yampa River, Colorado River near Cameo, Gunnison River, and San Juan River (from north to south, respectively). The most productive subbasin is the Colorado River near Cameo (USGS 09095500) in the northeastern part of the UCRB. This subbasin produces almost one quarter of the total naturalized runoff of the UCRB. It contains not only the mainstem but also several large tributaries, including the Eagle, the Roaring Fork, and the Blue. A little more than 30% of the UCRB flow is produced by the other three subbasins, and in total, about 55.5% of the total discharge of the UCRB is attributable to these four tributaries. Below, we discuss the nature of the long-term changes in these critical subbasins.

Figure 4 shows annual precipitation, ET, and runoff changes for all subbasins over the 1916–2014 study period. The top row is extracted from our baseline simulation, and the bottom row is from the T-detrend simulation. We note that although some subbasins appear similar between baseline and original maps, the

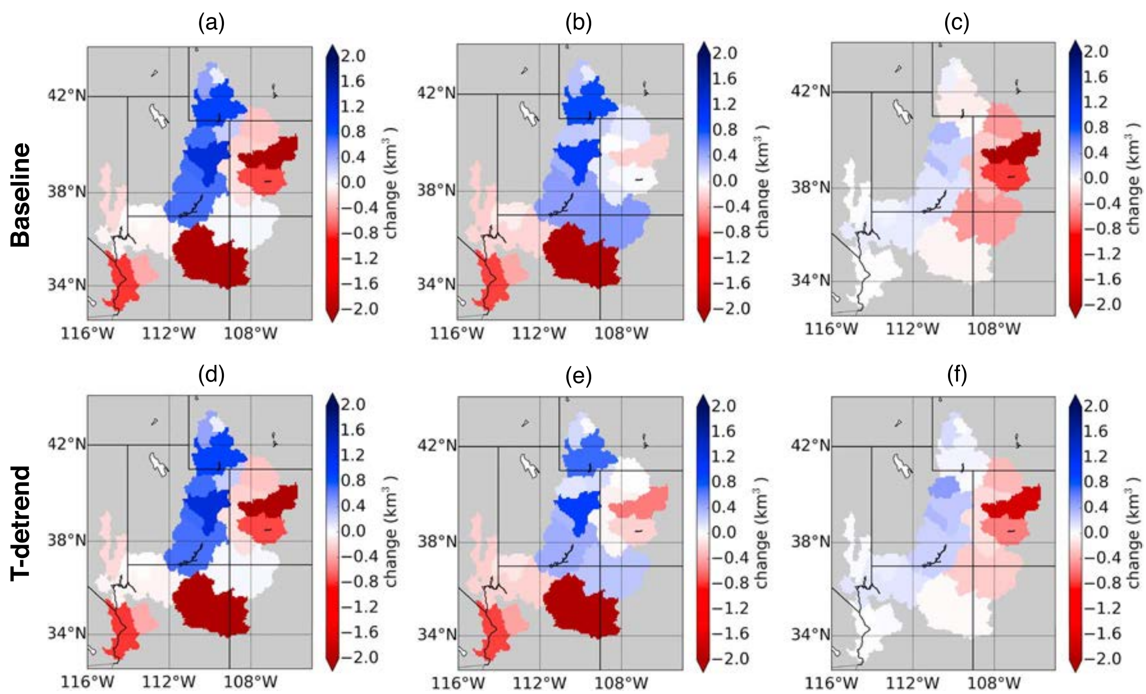


Figure 4. Spatial changes of (a) annual precipitation from gridded observations, (b) ET, and (c) runoff from baseline VIC simulation over 1916–2014 for CRB above Imperial Dam. Changes are calculated relative to the starting value of linear fits. Panels (d)–(f) are the same as (a)–(c), but variables are extracted from the T-detrend simulation. Panels (a) and (d) are identical.

Water Resources Research

10.1029/2018WR023153

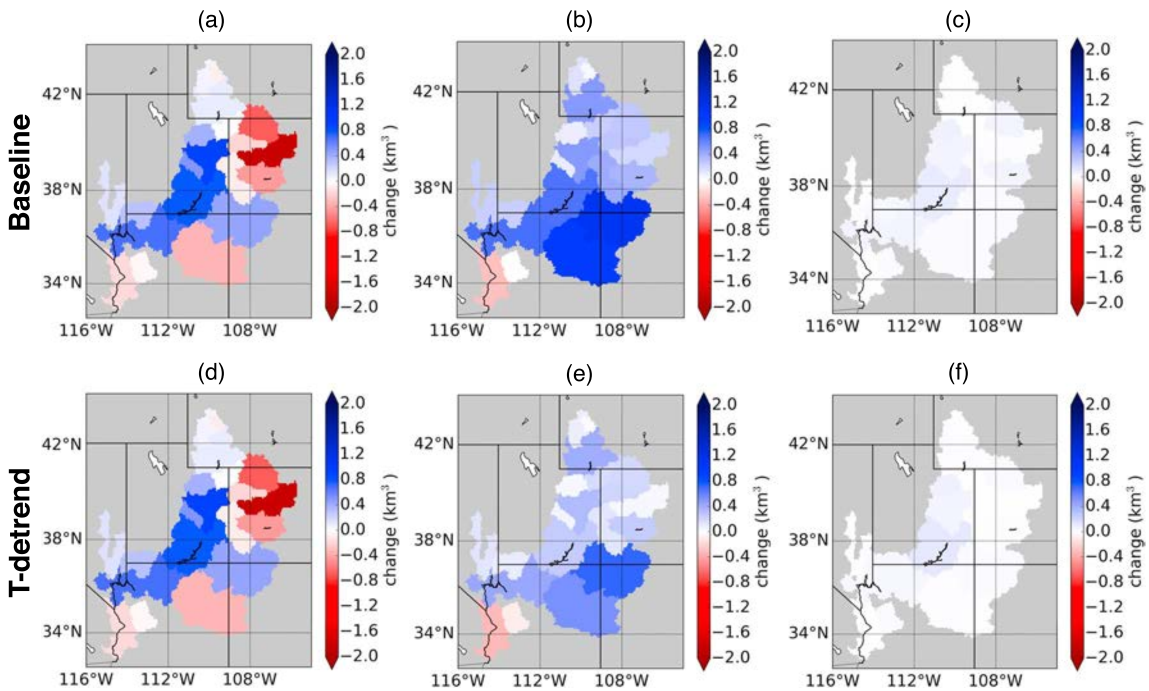


Figure 5. Same as Figure 4 but for winter (October–March).

numbers are more different than they might appear by visual inspection of the maps (Tables S3 and S4). We calculated the changes relative to the initial value of each linear fit, shown in Table 2. Figure 4a shows a noteworthy east-west dipole in the precipitation changes over time in the UCRB. In the UCRB, precipitation decreases have occurred mainly in the high runoff generating northeastern part of the basin, while several subbasins in the northwestern part of UCRB show long-term annual precipitation increases.

Precipitation declines have also occurred in the LCRB where little runoff occurs. These decreases in precipitation led to declines in ET and little change in subbasin runoff (Figures 4c and 4f), with negligible impact on total basin runoff (e.g., at Imperial Dam).

There are two subbasins in the northeastern part of the UCRB, which have relatively large annual precipitation decreases of -2.3 km^3 (Colorado River above Cameo) and -0.7 km^3 (Gunnison River) with a combined runoff decrease of -2.9 km^3 (supporting information). These are the same highly productive subbasins shown in Figure 1 and are a major driver of the overall annual runoff decline. Four basins in the northwestern part of UCRB with increasing precipitation (the Green River downstream portion along with its San Rafael River and Duchesne River tributaries; colored in deeper blues in Figure 4) have partially offset these long-term runoff declines by about 1.0 km^3.

Figures 5 and 6 are similar to Figure 4 but for winter (October–March) and summer (April–September), respectively. Winter runoff changes are small for both the baseline and T-detrend simulations, as most runoff occurs during the summer season. Although the total precipitation amounts are similar during warm and cold seasons, winter precipitation is much more important to the UCRB's runoff. Summer precipitation mainly contributes to ET rather than runoff, as high summer temperatures lead to large ET, especially at lower elevations. Winter precipitation in mountain headwater regions accumulates as snowpack and contributes mostly to RO rather than ET, when it melts.

The 1 April SWE trend plots for all the subbasins (Figures 3a and 3b) show that the four highly productive subbasins (Yampa River, Colorado River near Cameo, Gunnison River, and San Juan River) in the northeastern part of the basin that contribute much of the runoff losses in the UCRB have all experienced substantial SWE decreases. Those subbasins are also snow-dominant regions as indicated by Figure 3c. Figure 5a shows that winter precipitation has declined in all of the northeast UCRB subbasins except for the San Juan River, which shows a positive winter precipitation trend. Nonetheless, both SWE (Figure 3a) and annual RO (Figure 4c) in

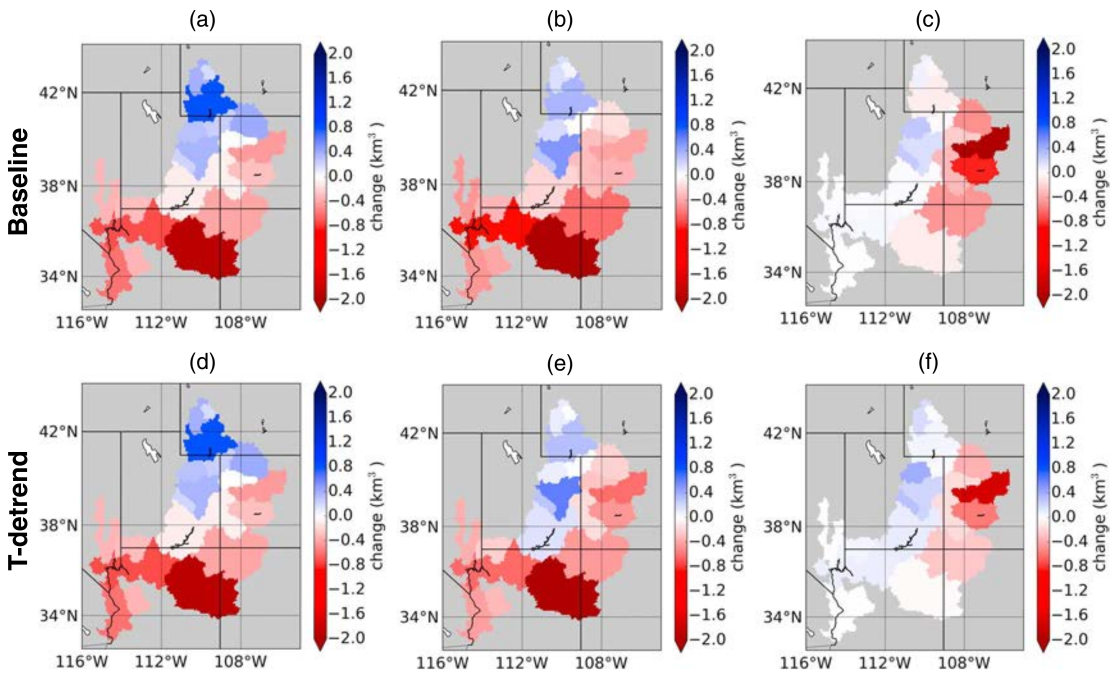


Figure 6. Same as Figure 4 but for summer (April–September).

the San Juan Basin are decreasing. The reason is that winter ET has increased substantially: ΔP_{winter} is +0.4 km^3, while long-term ΔET_{winter} is +1.1 km^3, with SWE decreasing by −0.7 km^3, or −30.1%. Declines in SWE in the other three basins, all of which experience declines in precipitation, are more severe and range from −46% to −49%. The increased winter ET, along with reductions in precipitation in these basins, explains the strongly decreasing SWE and substantially explain the declines in subbasin runoff.

As noted above, 53% (1.8 of 3.4) of the long-term runoff trend in the UCRB is related to warming temperatures. To dissect the remaining −1.6 km^3 (−47%) in the T-detrend simulation, we performed a P- and T-detrend experiment, in which we removed both the temperature and winter precipitation trend from the original input data set. Importantly, under this experiment the northeast UCRB basins see increased winter precipitation, while the northwest basins see decreased winter precipitation relative to the baseline and T-detrend simulations. Note, also, that we do not modify the summer precipitation, which increased over the study period. Under the P&T-detrend simulation, the UCRB's long-term runoff losses become −0.6 km^3 (1.0 km^3 less than the pure T-detrend and 2.8 km^3 less than the baseline). The residual −0.6 km^3 loss over the 1916–2014 period is attributable to increased winter ET. Section 4.2 below evaluates why ET_{winter} shows a positive trend given no P trend and no T trend. The total runoff decline of −3.4 km^3 can thus be attributed to warming (−1.8 km^3), insufficient P in the northeast part of CRB (−1.0 km^3), and increased winter ET (−0.6 km^3).

Summer precipitation and summer ET trend spatial plots (Figures 6a and 6d versus 6b and 6e) show similar patterns for both the baseline and T-detrend simulations: negative trends have occurred over the LCRB and the eastern UCRB, while some increases have occurred in the northwestern headwaters. The spatial patterns confirm that in the summer increases in precipitation drive increases in ET, while decreases in precipitation drive decreases in ET over both the LCRB and UCRB when surface air temperatures are relatively high.

In the UCRB the baseline simulation April–September runoff (Figure 6c), which constitutes almost three quarters of the CRB annual total, shows spatial patterns similar to the SWE spatial plots in Figure 3. Taken together, the figures show where water is stored as snow in the UCRB during winter in the cold, high-elevation headwater regions and how SWE then contributes to runoff in the following spring and summer. Over the last century, warming temperatures, reduced winter precipitation in the most productive mountain subbasins in the UCRB, and slight increases in winter ET (Figure 5b) lead to reduced SWE and consequently reduced runoff.

AGU 100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

10.1029/2018WR023153

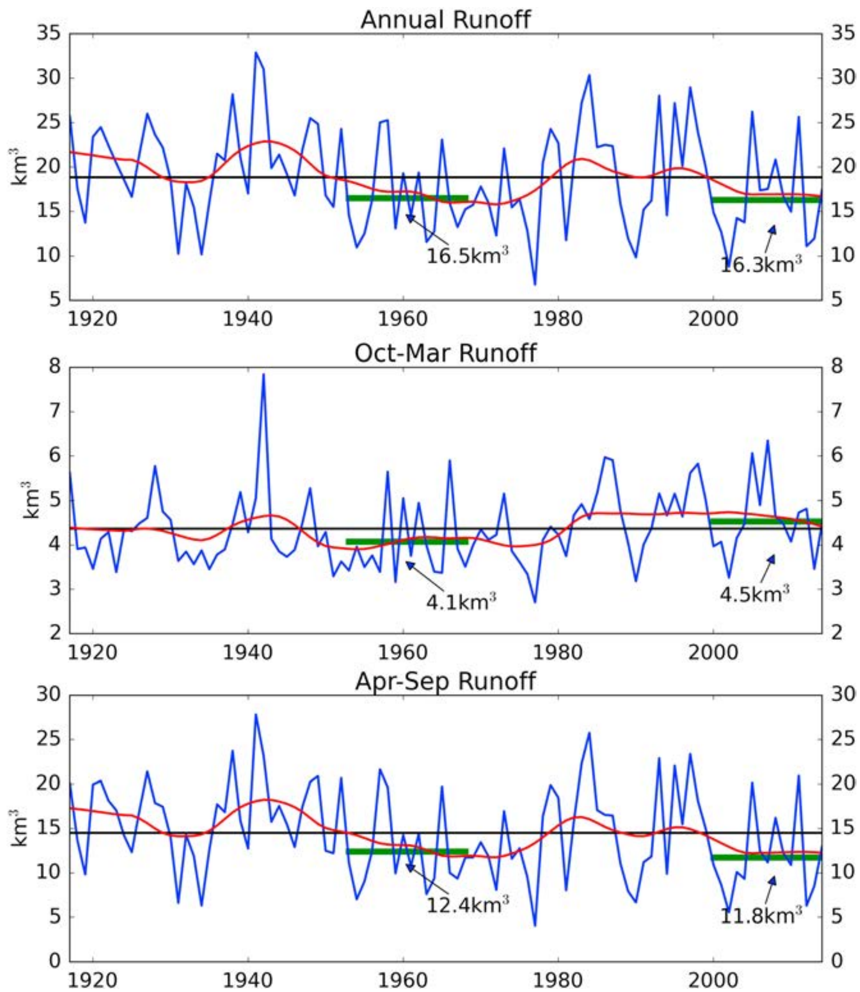


Figure 7. Time series of VIC simulations of annual runoff (top), winter runoff (middle), and summer runoff (bottom) at Lees Ferry (UCRB). The black horizontal lines are the long-term means, and red lines result from LOWESS filtering of VIC results.

In the LCRB, the annual precipitation, ET, and runoff plots show mostly P decreases, ET increases, and small RO changes (Figure 4). In winter, some P increases occur in the NW portion, ET increases everywhere except in the south, and RO has little change (Figure 5). Summer shows decreasing P, increasing ET, and little RO change (Figure 6).

3.3. Drought Comparisons

In order to examine the causes of the Millennium Drought, we compare the recent dry period from 2000 to 2014 (D2) with the 1953–1968 drought (D1). Figure 7 shows the time series of UCRB annual streamflow volume. Long-term averages are marked as the black horizontal baseline, and the Locally Weighted Scatterplot Smoothing (LOWESS) VIC streamflows are plotted in red. We report basin-wide (CRB, UCRB, and LCRB) annual average anomalies for four selected variables (P, SWE, ET, and RO) over the two drought periods in Table 3. Spatial anomaly plots by subbasin of P, SWE, ET, and RO for the 1953–1968 and 2000–2014 periods are shown in Figures 8 and 9.

Similar to the long-term trends discussed in section 3.3, comparison of the annual anomalies of precipitation, ET, and runoff during both droughts in Table 3 confirms that the UCRB dominates total basin-wide runoff production during drought periods as in the long term. In the Millennium Drought annual precipitation decreased more in the LCRB, which substantially reduced ET, but not runoff. This is a very large part of the overall basin-wide ET loss ($-7.9/-8.7$ km^3), but the LCRB ET does not make much difference to streamflow because most Lower Basin precipitation is converted to ET, drought or no drought. Since our primary interest is on the causes of declining runoff, we again focus on the UCRB.

Table 3
Annual Average Anomalies During the Midcentury Drought D1 (1953–1968) and Millennium Drought D2 (2000–2014) for CRB, UCRB, and LCRB

	P anomaly	P climatology	SWE anomaly	SWE climatology	ET anomaly	ET climatology	RO anomaly	RO climatology	T anomaly	T climatology
CRB-D1	−8.8	163.8	−2.9	19.3	−6.0	143.0	−2.7	20.7	0.0	8.5
CRB-D2	−11.4		−4.8		−8.7		−2.8		1.0	
UCRB-D1	−6.1	110.8	−2.7	18.7	−3.7	91.9	−2.4	18.9	0.1	5.6
UCRB-D2	−3.2		−4.4		−0.8		−2.6		1.0	
LCRB-D1	−2.7	53.0	−0.2	0.6	−2.3	51.1	−0.3	1.8	−0.2	13.0
LCRB-D2	−8.2		−0.4		−7.9		−0.2		1.0	

Note. Long-term climatologies are also provided. Results are relative to the 1916–2014 baseline simulation (Table 2); units are km^3 (except temperature is Celsius). The climatologies are extracted from the baseline simulation. (Table S6 includes the summer and winter anomalies for UCRB.)

Table 3 summarizes climate and hydrological differences and similarities between the two drought periods. In particular, UCRB RO anomalies for the two drought periods are quite similar (−2.4 versus −2.6 km^3; all the numbers are D1 versus D2 in this paragraph), whereas the SWE decrease is much greater in the Millennium Drought (−2.7 versus −4.4 km^3). Although the basin-wide annual (negative) precipitation anomaly in 1953–1968 is much less than the Millennium Drought (−8.8 versus −11.4 km^3), this order is reversed in the UCRB (−6.1 versus −3.2 km^3), where most runoff is generated. In the UCRB, the earlier 1953–1968 drought has less average annual precipitation than the Millennium Drought (104.6 versus 107.5 km^3), especially in winter when precipitation in the UCRB differentially contributes to runoff production, as discussed in section 3.2. Winter precipitation in the UCRB is 51.5 and 54.5 km^3 for 1953–1968 and 2000–2014, respectively, whereas summer precipitation is nearly identical (53.1 and 53.0 km^3; Table S6). Much higher temperatures (+0.1 versus +1.0 °C), less SWE (−2.7 versus −4.4 km^3), and more winter ET (+0.4 versus +1.8 km^3) are indicative of additional key differences between the two droughts.

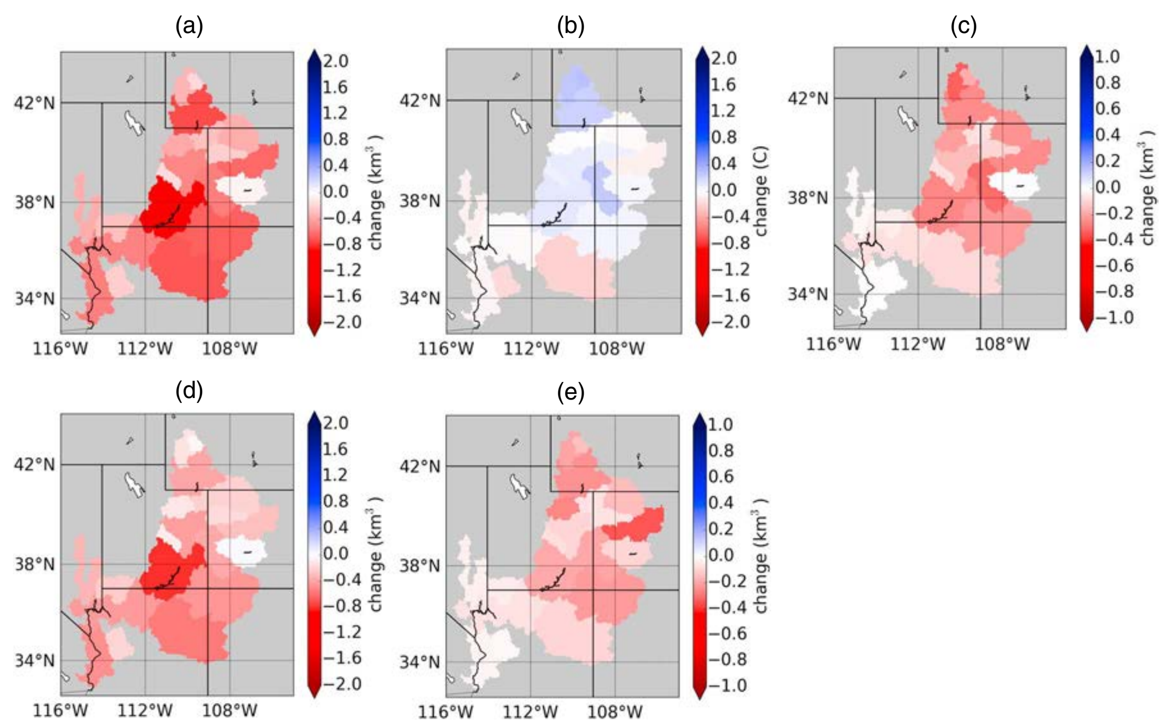


Figure 8. Average annual anomaly plots for each subbasin during the drought period 1953–1968. The variables in each panel are (a) precipitation, (b) temperature,(c) SWE, (d) ET, and (e) runoff (panels (c)–(e) are from VIC simulations).

Water Resources Research 10.1029/2018WR023153

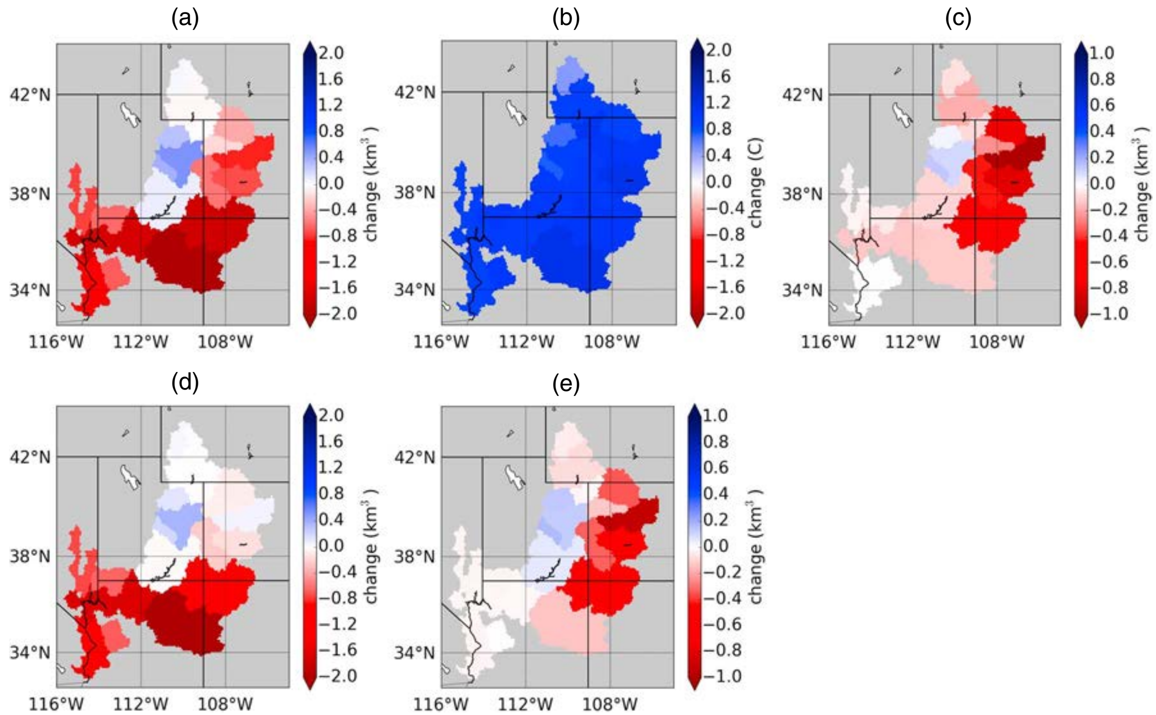


Figure 9. Same as Figure 8 but for 2000–2014 Millennium Drought.

Table 3 combined with Figures 8a–8e shows that the 1953–1968 drought mainly resulted from a spatially widespread and consistent negative precipitation anomaly across most of the UCRB. Temperatures were within 0.1 °C of the climatological mean. The corresponding ET and runoff anomalies therefore mostly reflect the precipitation reductions in each subbasin. SWE clearly decreases uniformly in almost all parts of the UCRB, as does runoff. Note that Figures 8a and 8c–8e all have similar patterns.

Interpretation of anomalies during the Millennium Drought is more complicated due to spatially heterogeneous conditions. Pervasive anomalously high temperatures, resulting in part from the long-term warming trend, which emerged around the 1970s and exacerbated by drought-specific warming, play a substantial role (Figure 9b). In addition, D2 average ET in the UCRB (Table 3 and Figure 9d), only 0.8 km^3 less than the climatological mean (despite drier conditions), combined with precipitation reductions in the most highly productive subbasins (Figure 9a) caused large runoff reductions in those key basins. In the UCRB, the western subbasins experienced positive precipitation anomalies with commensurate increases in ET. The northeastern subbasins where snow dominates and most of the UCRB runoff originates (Figure 3c) experienced negative precipitation anomalies but without commensurate decreases in ET, which acted to amplify the SWE reductions. Thus, Figures 9c and 9e show substantial declines in SWE and RO from these northeastern basins along with smaller declines and even some increases in SWE and RO from the northwestern basins. Unlike the 1950s drought, the spatial patterns in Figures 9a and9c-e are highly complex.

Eight basins—four from the highly productive northeast and four from the less productive northwest—provide additional insights into how spatially heterogenous precipitation, ET, and SWE combined to produce spatially variable runoff in the Millennium drought. The four most highly productive sub-basins (marked with red numbers in Figure 1) contributed more than 83% of the total -2.6-km^3/yr RO anomaly in the Millennium Drought; their contribution was only 34% of the -2.4-km^3/yr RO anomaly during 1953–1968 (numbers of each subbasin are provided in the supporting information). Four subbasins on the western side of the UCRB (draining the Uinta and Central Utah Mountains) had positive annual precipitation anomalies during 2000–2014 (leading to 0.5-km^3/yr positive RO anomaly), but that positive anomaly was more than canceled by other runoff-losing subbasins (-2.4 km^3 for the four highly productive northeastern basins). Compared with 1953–1968, precipitation anomalies were much more uneven in the Millennium Drought. The

 10.1029/2018WR023153

relatively evenly distributed positive +1 °C temperature anomalies lead to more winter ET (+0.8 km^3, 3.7% of the annual streamflow) and reduced SWE (−4.8 km^3, 23.0% of the annual streamflow), exacerbating the precipitation reductions over the UCRB.

By combining our T-detrend and P&T-detrend simulations, we can gain additional insights into the Millennium Drought when used in a similar fashion to our long-term trend analysis. Comparing the two simulations suggests that the temperature anomaly was responsible for −1.4 km^3 of the Millennium Drought runoff loss (total is −2.6 km^3), while the precipitation deficit caused −1.0 km^3 of the remaining −1.2 km^3 runoff loss. The average runoff in the P&T-detrend results is quite close to the long-term climatology (P&T-detrend: 18.7 km^3, climatology: 18.9 km^3, less than 1% difference), suggesting that the model precipitation and temperature changes are faithfully capturing the drought causes.

4. Interpretation and Discussion

4.1. Long-Term Trends

The Colorado River is snow-dominated, although only about 18% of the entire basin area accumulates enough SWE to produce substantial spring and summer RO (see 1 April SWE climatology >50 mm as shown in Figure 3c). Basin-wide 1 April SWE is approximately 20 km^3, which is close to the annual runoff at Lees Ferry. Li et al. (2017) show that for the UCRB, SWE accounts for 71% of annual runoff on average. Summer (April–September) RO constitutes almost ¾ of the total annual RO in both the UCRB and the entire basin. Clearly then, winter precipitation (and hence spring SWE) is closely linked to annual runoff changes. Although the overall winter precipitation trend from 1916 to 2014 is not significant over the entire UCRB (−0.2%, Table 2), uneven spatial distribution causes important winter precipitation decreases in several of the snow-dominant most runoff-productive headwater subbasins. Warming temperatures over our nearly hundred-year period of record in the UCRB (annual long-term ΔT is 1.8 °C as in Figure 2) induce −1.8 km^3 (53%) of the annual runoff losses totaling −3.4 km^3. The remaining −1.6 km^3 results from negative winter precipitation anomalies, mostly in the northeastern subbasins of UCRB (−1.0 km^3) and increasing winter ET (−0.6 km^3).

4.2. Winter ET and Sublimation

We found that increasing winter ET in both the baseline (4.9 km^3) and the T-detrend (2.9 km^3, Table 2) comes mainly from snow sublimation. In the T-detrend simulation, the November to February long-term change of UCRB sublimation is 2.2 km^3 (75.9% of the 2.9-km^3 ΔET_{winter} increase) with the remaining 0.7 km^3 from increased evaporation in March. A possible cause of these trends in individual months was our approach using annual rather than seasonal (e.g., monthly) trend removal. Therefore, we performed another simulation with temperature detrended on a grid cell by grid cell basis for each month, instead of annually. This resulted in a considerable decrease in the March ET trend, which apparently was caused primarily by the increasing annual temperature trend. However, snow sublimation from October to February still showed increasing trends in this monthly T-detrend simulation. We were therefore left to explain the positive trends in snow sublimation over October–February given neither temperature nor precipitation trends.

We considered other factors that can influence the sublimation process in VIC. We found that the winter months had positive trends in surface aerodynamic resistance (AR), which leads to positive trend in surface snow sublimation. The AR trend was traced to the wind forcings in our VIC input data set, which are based on National Centers for Environmental Prediction /National Center for Atmospheric Research reanalysis, the record for which starts in 1949. Following Livneh et al. (2013), absent wind data prior to 1948, the earlier values were set to their monthly climatological averages. Although this approach did not result in a trend in wind over the 1916–2014 period, the nonlinear relationship between AR and wind speed results in larger AR values occurring after 1948 and thus results in the long-term increasing sublimation trend. While the resulting overall RO negative trend associated with this effect was modest (−0.6 km^3), we changed our pre-1949 wind values by randomly sampling from the later (post-1948) record. This resulted in the long-term UCRB annual RO trend becoming essentially zero in a new P&T detrend simulation. Livneh et al. (2013) reported that using wind climatology had only small impacts on their long-term mean RO, but in the case of the relatively dry CRB, the abrupt change in wind variability created artificial sublimation that was not negligible.

Water Resources Research 10.1029/2018WR023153

4.3. Drought Comparisons

Compared to the 1953–1968 drought, the causes of the Millennium Drought are more complicated. During the 1953–1968 drought, annual precipitation anomalies were negative across the entire CRB (Figure 8a) and temperature was close to its long-term mean (Figure 8b). Subbasin runoff anomalies, as well as SWE and ET anomalies, all responded primarily to the precipitation deficits. In contrast, the upper and lower parts of CRB behaved much differently during the Millennium Drought. In the UCRB, both winter and summer precipitation during 2000–2014 are just slightly below their climatologies (54.4 km^3/winter compared to 55.8 km^3/winter long-term mean) and 53.0 km^3/summer (compared to 55.0 km^3/summer long-term mean). The UCRB received approximately normal (slightly negative anomalies) winter precipitation, which was clearly higher than P_{winter} during 1953–1968 as noted in section 3.3, but produced less annual runoff (16.3 km^3/yr versus 16.5 km^3/yr).

The situation is reversed, however, if the temperature trend is removed. In this case the 1953–1968 drought becomes worse than the Millennium Drought. In the T-detrend simulation, the average annual runoff for the UCRB during 1953–1968 and 2000–2014 were 17.2 and 17.7 km^3/yr, respectively (baseline annual runoff climatology is 18.9 km^3). Therefore, the warming temperature accounts for 54% of the annual runoff anomaly during the Millennium Drought (-1.4 km^3/yr of -2.6 km^3/yr), which is very close to its 53% contribution to the long-term decreasing runoff trend. The other half of the runoff deficit was caused by UCRB's negative winter precipitation anomalies in the northeastern part of the basin where the highest runoff-generating subbasins are. The winter ΔP over 2000–2014 in those four highly productive subbasins was -2.4 km^3/yr, much larger (in absolute value) than ΔP_{winter} over 1953–1968, -0.9 km^3/yr. Exacerbated by above normal winter temperature in the baseline simulation, the UCRB winter ET anomaly over 2000–2014 was 1.8 km^3/yr and ΔSWE is -4.4 km^3/yr (23.7% less compared to the climatology).

These results demonstrate that warming temperature was a major driver for the UCRB's runoff shortage over the Millennium drought, in agreement with Udall and Overpeck (2017). In the Lower Basin, annual precipitation had very serious negative anomalies across the entire LCRB as shown in Figure 9a: all subbasins exhibited pronounced negative anomalies. While temperatures were also higher across the LCRB, there is no need to invoke a temperature forcing to explain the drought. As noted above, though, these LCRB precipitation anomalies have little effect on RO.

Using the Millennium Drought anomalies, we can estimate the runoff-precipitation-elasticity relationships as follows: the baseline average annual runoff for the UCRB is 18.9 km^3, and the T-detrend runoff is 17.7 km^3; therefore, the 1.2 km^3 runoff decrease apparently is attributable to precipitation. Over 2000–2014 annual precipitation in the UCRB was 107.5 km^3 and the climatology was 110.8 km^3/yr, so ΔP/P is -0.029. The implied elasticity is 2.12 ($\Delta RO \cdot RO^{-1} \cdot \Delta P^{-1} \cdot P = -0.0616/-0.0291$), which is in good agreement with Vano et al. (2012).

4.4. Uncertainties

The results and analysis we have presented to this point are based on VIC simulations forced by the extended H&L data set. The robustness of the conclusions is potentially dependent on both the forcings and model performance. In order to examine the robustness of our results, we performed an exploratory uncertainty analysis of both the model forcings and hydrological model.

First, we compared the H&L forcings to two other widely used gridded climate datasets: Precipitation Regressions on Independent Slope Method (PRISM; Di Luzio et al., 2008) and Livneh (Livneh et al., 2013). Over the UCRB, trends in annual precipitation of these three data sets (H&L, PRISM, and Livneh) have long-term annual trends ranging from -6% to +2%, and for winter precipitation from -10% to +6%. As for the temperature, on an annual basis the positive trend over UCRB ranges from 1.0 °C to 1.4 °C and for winter temperature from 1.0 °C to 1.6 °C. As noted in the supporting information (Table S7), the H&L temperature trends generally are larger than for the other two data sets (also see section 2.1; the VIC temperature trend is not the same as the H&L trend but rather is somewhat larger, approximately 0.4 °C, as it results from energy budget closure in the model). The relatively large negative precipitation trend in Livneh is mostly attributable to large annual precipitation early in the record and in likelihood is traceable to the relatively liberal criterion that data set uses to allow entry of stations with relatively short record lengths.

Water Resources Research 10.1029/2018WR023153

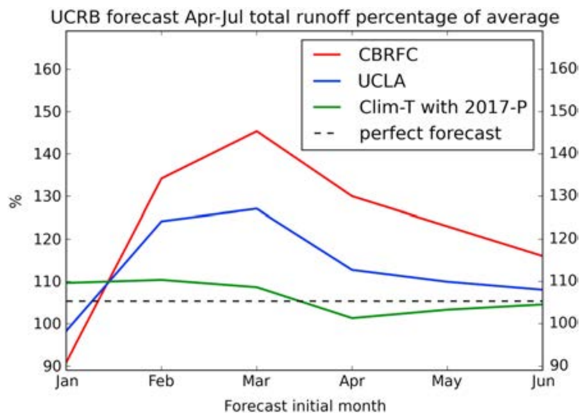


Figure 10. April–July 2017 streamflow forecasts at Lees Ferry initialized on the first day of each month expressed as percentages relative to 1981–2010 climatology. Red line represents the official forecasts published by CBRFC; blue line represents equivalent VIC reforecasts; green line is forecast with perfect precipitation forecast and temperature climatology. The horizontal dashed line is from a forecast with perfect precipitation and temperature.

Our choice of the H&L data set is based on its relationship with the HCN station data (to which its decadal variability is controlled; see Hamlet & Lettenmaier, 2005). The HCN data have been carefully quality controlled and in this sense arguably are more appropriate for trend-related studies than are the other two data sets (or for that matter, other data sets we might have chosen). We evaluated the H&L long-term temperature trend over UCRB (1.4 °C increase) in comparison with the simple average over all HCN stations in the UCRB (also 1.4 °C increase; identical to two significant figures). On this basis, and given the criteria used in construction of the H&L data set, we believe that it is most appropriate for our purposes. We do not believe that other methods that, for instance, might use multiple ensembles and effectively average either inputs to our outputs from our hydrological model would be appropriate given the objectives of our analysis.

As for hydrological models, we extracted the Noah-MP and VIC results from the UCLA Drought Monitor (Xiao et al., 2016) for model comparison (note that the forcings for the UCLA Drought Monitor are different than H&L but are common to the two models). Over the entire Upper Basin and the four most productive subbasins we identified, the long-term trends in Noah-MP and VIC runoff are generally consistent, for instance, for the entire UCRB (VIC: -3.5 km^3/yr; Noah-MP: -4.3 km^3/yr); see also subbasin trends shown in Figure S2. Although different models would no doubt produce somewhat different results, the fact that VIC and Noah-MP, which have essentially no common heritage, produce similar trends gives us some confidence that our results are reasonable model independent.

This uncertainty analysis improves the confidence in our conclusions. Nonetheless, more work could be done along these lines. For example, there is substantial uncertainty in the gridded forcing data sets we used, which are sparse and especially rare at high elevations. More sophisticated methods could be used to represent the uncertainty in the gridded data sets (aside from testing sensitivity to different data sets, as we have done). Furthermore, land surface models, which simulate complex systems, contain approximations and uncertainties that produce errors that are difficult to represent in analyses such as ours. Thus, given computational constraints, less than complete understanding of physical processes and limited observation resolutions, state-of-the-art land surface models will inevitably produce somewhat uncertain results. We acknowledge these uncertainties, which no doubt will motivate future work. We nonetheless argue that our results in the larger sense transcend the effects of these uncertainties, in particular given their robustness with respect to models and model forcing data sets.

5. The 2017 Streamflow Forecast

The Colorado Basin River Forecast Center (CBRFC) produces seasonal (April–July) streamflow forecasts starting about 1 January with monthly updates for the CRB using its Ensemble Streamflow Prediction (ESP) approach (Werner & Yeager, 2013) based on the Sacramento Soil Moisture Accounting model (Burnash et al., 1973). General characteristics of Sacramento and VIC simulations, and hence ESP forecasts, are roughly similar (Vano et al., 2012). The CBRFC forecast utilizes historical meteorological forcings for 1981–2010 to generate an ensemble of future streamflow series given hydrological conditions (soil moisture and SWE) on the forecast initiation date (e.g., 1 April), which are taken from a historical model simulation. We analyzed the forecasts issued on the first day of each month in 2017 from January to June. The official CRBFC forecast for the UCRB 2017 April–July streamflow (natural flow at Lees Ferry) decreased dramatically from much above normal on 1 January as the runoff season progressed. Some media reports attributed these decreases to anomalously warm late winter and spring conditions and drew parallels between water year 2017 conditions and the long-term trends analyzed above, especially in temperature.

We evaluated the causes of the changes in the 2017 forecasts using the same ESP approach as used by CRBFC but using the VIC rather than the Sacramento model. Because the ESP method requires near-real-time records and meteorological forcings, we used the UCLA/UW Drought Monitor data set (see Xiao et al., 2016) to perform the retrospective ensemble forecasts.

AGU 100 ADVANCING EARTH AND SPACE SCIENCE
Water Resources Research 10.1029/2018WR023153

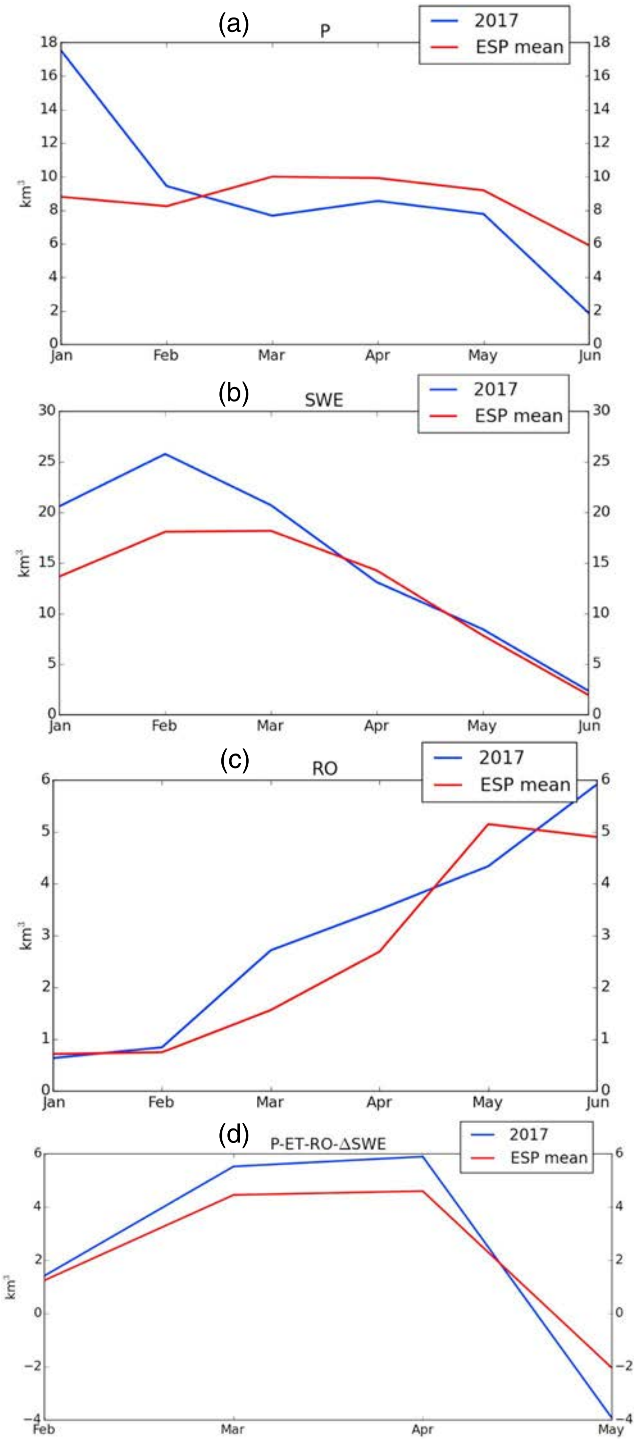


Figure 11. Monthly time series plots of (a) precipitation, (b) SWE, (c) runoff, and (d) soil moisture change. The blue line is the 2017 forecast; red line is historical climatology.

Figure 10 shows the predicted naturalized streamflow at Lees Ferry for each forecast initialized on the first day of each month. The red line shows the official forecasts produced by CRBFC, and the blue line is the average of the ensemble predictions generated using the UCLA/UW drought monitor data set. The green line shows the streamflow predictions that would have been made with a perfect precipitation forecast (they come from a VIC simulation with observed 2017 precipitation) but with temperature ensembles taken from observations for 1981–2010.

We performed this experiment to separate the effect of precipitation and temperature on the ESP results. In interpreting the forecasts, it is important to note that the forecast period is the same (April–July) for all forecasts, even though for post 1 April forecasts, part of the forecast period has already occurred, and some of the water literally has already gone *under the bridge*. It is clear that both the red and blue curves exhibit peaks around February–March with forecasts declining later. The CBRFC forecasts are higher than those made with VIC, which most likely is attributable to a different hydrologic model and different model forcing data sets; however, both sets of forecasts have the same general patterns. Also, both sets of forecasts are still above climatology for the last forecast (1 June), due to anomalously high SWE early in the forecast period. From the green line we can infer that the differences between the perfect precipitation forecasts initialized at each time and climatology are considerably smaller than the differences between either of the ESP forecast sets and climatology.

Given the perfect precipitation forecasts, the forecasts vary from 100% to 110% of the mean, which are close to the true value (observed flow relative to climatology) of 105.3%. Anomalously warm temperatures in February and March 2017 (plots are not shown here) caused some error in the forecasts: the streamflow forecasts initialized on 1 February and 1 March are both higher than observed because the climatology is cooler, but the differences are modest. In general, warm temperatures lead to less runoff and vice versa but this appears not to be the primary explanation for the rapid decrease in the two ESP ensemble means through the winter and early spring.

Figure 11 shows the monthly time series plots of precipitation, SWE, runoff, and soil moisture change (P-ΔSWE-ET-RO) for the UCRB for both 2017 and climatology from 1981 to 2010. The precipitation plot (Figure 11a) shows that the UCRB received anomalously high precipitation in January and February (with the highest anomaly in January), but the precipitation later in the forecast period was less than climatology. The direct effect is that in February 2017 there was a large positive SWE anomaly (Figure 11b), but the anomaly decreased thereafter. This explains why the ESP forecast peak was in February.

The RO time series plot in Figure 11c is more complicated: RO production was anomalously high in March, April, and June but lower than climatology in May. The question of interest is where did the snowpack that accumulated in January and February go? From Figure 11b, about 5 km^3 of SWE melted in February and March. However, precipitation anomalies were in the range (negative) 2–4 km^3 for each month from March 2017 on. The fact that 2017 ET during the forecast period was close to climatology (plot not shown) suggests that enhanced early season snowmelt supplied water to the soil column, but reduced subsequent precipitation hindered runoff production.

Figure 11d shows the modeled water balance for the soil column (P-ET-RO-ΔSWE). Figure 11d shows that ΔSMs in March and April are larger than climatology, but not by much. Furthermore, runoff generation

Water Resources Research 10.1029/2018WR023153

(Figure 11c) is above climatology during that period. However, as the precipitation deficit persisted into late spring and summer, SM began to decrease substantially. The RO actually produced was less than the early forecasts (initialized in February and March) because the ESP ensemble mean effectively corresponds to normal precipitation, which is higher than actually occurred from late winter on in 2017. In summary, the sharp reduction in forecasts through late winter and spring appears to be primarily related to negative anomalies in late winter precipitation, with anomalously warm late winter temperatures having a secondary effect.

6. Summary and Conclusions

Both long-term (~100 years) trends in streamflow and comparisons of two major drought periods (1953–1968 and Millennium) point to ongoing changes in the relative control of precipitation and temperature on the river's runoff. Udall and Overpeck (2017) have argued that a transition is occurring, which is especially evidenced by the different responses of the 1953–1968 and ongoing Millennium drought to precipitation and temperature anomalies. We find that while there is strong evidence for such a transition, the situation is complicated by spatial variations across the subbasins that contribute most to both long-term trends and drought variations in the basin, as well as to seasonal differences in temperature and precipitation trends and anomalies. Specifically, we conclude the following:

1. Over the UCRB (which produces about 90% of the entire basin's runoff), the long-term 1916–2014 decreasing trend of annual runoff is -3.4 km^3 (or -16.5% over the entire record). The increasing trend in annual temperature averaged over the basin over the same period has been 1.8 °C. When the annual temperature trend is removed, the negative trend in annual runoff becomes -1.6 km^3, which suggests that warming caused a little over half (1.8 km^3 or 53%) of the annual runoff trend. Four snow-dominated subbasins in the northeast part of the basin that in combination account for over half of the UCRB runoff have experienced modest declines in winter precipitation, which account for a substantial part of the UCRB runoff trend (-1.0 km^3) that is not attributable to warming. The remainder of the runoff loss (-0.6 km^3) is mostly associated with increased winter ET (mainly snow sublimation).
2. Compared to the 1953–1968 drought, which was caused by a basin-wide precipitation deficit, the Millennium Drought reflects a strong influence of warmer temperatures. The UCRB experienced low streamflow (2.6 km^3/yr below average, slightly more severe than the 2.4 km^3/yr negative anomaly for 1953–1968) during the Millennium Drought years (2000–2014 in our analysis). The four subbasins in the northeastern part of the UCRB with the largest negative long-term trends are also the major contributors to Millennium Drought runoff anomalies. The decrease of runoff for the Colorado River near Cameo was especially prominent—it alone accounts for over half of the 2000–2014 runoff anomalies. Although subbasins with positive runoff anomalies on the south side of Uinta Mountains such as the Duchesne and San Rafael Rivers counteract some of the deficit, UCRB Millennium Drought runoff was well below normal due primarily to deficits in the northeastern subbasins.
3. During the Millennium Drought years, the UCRB's precipitation was close but slightly below the long-term climatology (annual: 107.5 versus 110.8 km^3/yr; winter: 54.5 versus 55.8 km^3/yr). However, Millennium Drought annual precipitation was higher than the average for 1953–1968 (104.6 km^3/yr). Winter precipitation during the Millennium Drought was also higher than in the 1953–1968 drought; only summer precipitation was slightly lower. However, the highly productive subbasins in the northeastern portion of the UCRB had comparatively large winter precipitation deficits during 2000–2014, which resulted in 1.0 km^3/yr of the UCRB streamflow total reductions (2.6 km^3/yr) that were not attributable to warming. Warming temperatures caused 1.4-km^3/yr runoff losses.
4. By reforecasting the 2017 April–July natural streamflow at Lees Ferry using the same ESP approach used by CBRFC, we reproduce similar reductions in forecasted runoff to the CBREFC forecasts through the forecast season in what started as a large positive forecast anomaly in April–July runoff forecast on 1 January. The April–July forecast peaked around March 2017 due to abundant SWE in the UCRB induced by high early winter precipitation. Anomalously high snowmelt increased runoff in March and April. However, precipitation from March on continued below normal, and the forecast trended downward in the later months, eventually ending with only modestly above normal April–July runoffs. Anomalously warm temperatures from late winter on in 2017 aggravated the situation but appear not to be the major cause of the forecast declines, which rather was relatively dry conditions from mid-winter on.

Water Resources Research 10.1029/2018WR023153

Given the importance of the Colorado River Basin to the rapidly growing U.S. Southwest, others likely will address the causes of the both the long-term and recent changes in CRB runoff, and the future implications of these findings as the 21st century continues to warm. As we noted in section 4.4, our results and conclusions are tightly linked with the forcing data set and the model (s) we used. The gridded forcings (for precipitation and temperature, as well as other variables derived from them) propagate through the hydrologic modeling and in turn our diagnosis of runoff changes. We opted to use the Hamlet and Lettenmaier (2005) forcing data set because it is closely linked to the U.S. Hydroclimatic Network (HCN; Easterling et al., 1996), which is based on a set of stations with relatively complete long-term records that have been corrected for station moves and instrument changes. Nonetheless, the stations included in HCN are predominantly at low elevations, and various avenues (e.g., assimilation of available surface and/or satellite observations into a coupled land/atmosphere model) could be pursued to better represent the role of high-elevation climatic changes, which may well not have occurred in concert with changes at lower elevations. We also note in section 4.4 (and explore, via limited experiments with a second model, Noah-MP) the possible sensitivity of our results to the form of the LSM, but much more could be done in this respect. Finally, we note that all of our experiments are offline; hence, we partition CRB runoff changes into those associated with warming temperatures and other factors (mostly precipitation changes); however, these multivariate changes may well be linked in ways that we have not explored. For instance, the modest changes in precipitation that we examined may be coupled with temperature changes and/or changes in the atmospheric radiative balance, and such linkages certainly are worth exploring.

Acknowledgments
The research on which this paper was based was supported in part by the National Oceanic and Atmospheric Administration's Modeling, Analysis, Prediction, and Projections Program (MAPP) under award NA14OAR4310293 to the University of California, Los Angeles. Model simulation archive is https://doi.org/10.6084/m9.figshare.6995012.v1; contact muxiao@ucla.edu for questions about the data.

References

Andreadis, K. M., Storck, P., & Lettenmaier, D. P. (2009). Modeling snow accumulation and ablation processes in forested environments. *Water Resources Research*, *45*, W05429. https://doi.org/10.1029/2008WR007042

Barnett, T. P., & Pierce, D. W. (2009). Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(18), 7334–7338. https://doi.org/10.1073/pnas.0812762106

Burnash, R. J. C., Ferral, R. L., & McGuire, R. A. (1973). A generalized streamflow simulation system—Conceptual modelling for digital computers (204 pp.).

Christensen, N. S., & Lettenmaier, D. P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth System Sciences Discussions*, *11*(4), 1417–1434. https://doi.org/10.5194/hess-11-1417-2007

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, *62*(1-3), 337–363. https://doi.org/10.1023/B:CLIM.0000013684.13621.1f

Cohen, M., Christian-Smith, J., & Berggren, J. (2013). Water to supply the land: Irrigated agriculture in the Colorado River Basin. Retrieved from http://water.usgs.gov/watercensus/colorado.html

Dawadi, S., & Ahmad, S. (2012). Changing climatic conditions in the Colorado River Basin: Implications for water resources management. *Journal of Hydrology*, *430-431*, 127–141. https://doi.org/10.1016/j.jhydrol.2012.02.010

Di Luzio, M., Johnson, G. L., Daly, C., Eischeid, J. K., & Arnold, J. G. (2008). Constructing retrospective gridded daily precipitation and temperature datasets for the conterminous United States. *Journal of Applied Meteorology and Climatology*, *47*(2), 475–497. https://doi.org/10.1175/2007JAMC1356.1

Easterling, D. R., Karl, T. R., Mason, E. H., Hughes, P. Y., & Bowman, D. P. (1996). United States Historical Climatology Network (US HCN), monthly temperature and precipitation data (280 pp.). http://cdiac.esd.ornl.gov/ndps/ushcn/abstract_r3.html

Hamlet, A. F., & Lettenmaier, D. P. (2005). Production of temporally consistent gridded precipitation and temperature fields for the continental United States. *Journal of Hydrometeorology*, *6*(3), 330–336. https://doi.org/10.1175/JHM420.1

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters*, *44*, 6163–6172. https://doi.org/10.1002/2017GL073551

Liang, X., & D. Lettenmaier (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysics*. *99*, 14,415–14,428. https://doi.org/10.1029/94JD00483/full (Accessed April 16, 2014).

Livneh, B., Rosenberg, E. A., Lin, C., Nijssen, B., Mishra, V., Andreadis, K. M., et al. (2013). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: Update and extensions. *Journal of Climate*, *26*(23), 9384–9392. https://doi.org/10.1175/JCLI-D-12-00508.1, http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00508.1 (Accessed October 22, 2014).

McCabe, G. J., & Wolock, D. M. (2007). Warming may create substantial water supply shortages in the Colorado River basin. *Geophysical Research Letters*, *34*, L22708. https://doi.org/10.1029/2007GL031764

McCabe, G. J., Wolock, D. M., Pederson, G. T., Woodhouse, C. A., & McAfee, S. (2017). Evidence that recent warming is reducing upper Colorado river flows. *Earth Interactions*, *21*(10), 1–14. https://doi.org/10.1175/EI-D-17-0007.1

Mote, P. W., Hamlet, A. F., Clark, M. P., & Lettenmaier, D. P. (2005). Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society*, *86*(1), 39–50. https://doi.org/10.1175/BAMS-86-1-39

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018). Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, *1*(1), 2. https://doi.org/10.1038/s41612-018-0012-1, http://www.nature.com/articles/s41612-018-0012-1

Prairie, J., & Callejo, R. (2005). Natural flow and salt computation methods, calendar years 1971-1995. Bureauof Reclamation, Salt Lake City, Utah and Boulder City, Nevad, Final, 1–112. Retrieved from http://digitalcommons.usu.edu/govdocs/135/%5Cnpapers2://publication/uuid/6183E843-86FF-4150-9535-C0407CB5477D

Rajagopalan, B., Nowak, K., Prairie, J., Hoerling, M., Harding, B., Barsugli, J., et al. (2009). Water supply risk on the Colorado River: Can management mitigate? *Water Resources Research*, *45*, W08201. https://doi.org/10.1029/2008WR007652

Water Resources Research 10.1029/2018WR023153

Reynolds, L. V., Shafroth, P. B., & LeRoy Poff, N. (2015). Modeled intermittency risk for small streams in the Upper Colorado River Basin under climate change. *Journal of Hydrology*, *523*, 768–780. https://doi.org/10.1016/j.jhydrol.2015.02.025

Rosenberg, E. A., Clark, E. A., Steinemann, A. C., & Lettenmaier, D. P. (2013). On the contribution of groundwater storage to interannual streamflow anomalies in the Colorado River basin. *Hydrology and Earth System Sciences*, *17*(4), 1475–1491. https://doi.org/10.5194/hess-17-1475-2013

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall' Stau Pranab Kumar Sen. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.2307/2285891

Theil, H. (1950). A rank-invariant method of linear and polynomial regression analysis I. *NederlandseAkademie Wetenchappen*, *23*, 386–392. https://doi.org/10.1007/978-94-011-2546-8

U.S. Department of Interior, Bureau of Reclamation (1983). DRAFT Colorado River Simulation System Hydrology Data Base.

Udall, B., & Overpeck, J. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*, 2404–2418. https://doi.org/10.1002/2016WR019638

Vano, J. A., Das, T., & Lettenmaier, D. P. (2012). Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature*. *Journal of Hydrometeorology*, *13*(3), 932–949. https://doi.org/10.1175/JHM-D-11-069.1

Vano, J. A., Udall, B., Cayan, D. R., Overpeck, J. T., Brekke, L. D., Das, T., et al. (2014). Understanding uncertainties in future Colorado River streamflow. *Bulletin of the American Meteorological Society*, *95*(1), 59–78. https://doi.org/10.1175/BAMS-D-12-00228.1

Werner, K., & Yeager, K. (2013). Challenges in forecasting the 2011 runoff season in the Colorado Basin. *Journal of Hydrometeorology*, *14*(4), 1364–1371. https://doi.org/10.1175/JHM-D-12-055.1

Woodhouse, C. A., Pederson, G. T., Morino, K., Mcafee, S. A., & Mccabe, G. J. (2016). Increasing influence of air temperature on upper Colorado River streamflow. 1–8. https://doi.org/10.1002/2015GL067613

Wu, H., Kimball, J. S., Li, H., Huang, M., Leung, L. R., & Adler, R. F. (2012). A new global river network database for macroscale hydrologic modeling. *Water Resources Research*, *48*, W09701. https://doi.org/10.1029/2012WR012313

Xiao, M., Nijssen, B., & Lettenmaier, D. P. (2016). Drought in the Pacific Northwest, 1920-2013. *Journal of Hydrometeorology*, *17*(9), 2391–2404. https://doi.org/10.1175/JHM-D-15-0142.1

Sustainable water deliveries from the Colorado River in a changing climate

Tim P. Barnett[1] and David W. Pierce

Division of Climate, Atmospheric Science, and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, CA 92093-0224

Edited by Peter Gleick, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, and approved March 6, 2009 (received for review December 15, 2008)

The Colorado River supplies water to 27 million users in 7 states and 2 countries and irrigates over 3 million acres of farmland. Global climate models almost unanimously project that human-induced climate change will reduce runoff in this region by 10–30%. This work explores whether currently scheduled future water deliveries from the Colorado River system are sustainable under different climate-change scenarios. If climate change reduces runoff by 10%, scheduled deliveries will be missed ≈58% of the time by 2050. If runoff reduces 20%, they will be missed ≈88% of the time. The mean shortfall when full deliveries cannot be met increases from ≈0.5–0.7 billion cubic meters per year (bcm/yr) in 2025 to ≈1.2–1.9 bcm/yr by 2050 out of a request of ≈17.3 bcm/yr. Such values are small enough to be manageable. The chance of a year with deliveries <14.5 bcm/yr increases to 21% by midcentury if runoff reduces 20%, but such low deliveries could be largely avoided by reducing scheduled deliveries. These results are computed by using estimates of Colorado River flow from the 20th century, which was unusually wet; if the river reverts to its long-term mean, shortfalls increase another 1–1.5 bcm/yr. With either climate-change or long-term mean flows, currently scheduled future water deliveries from the Colorado River are not sustainable. However, the ability of the system to mitigate droughts can be maintained if the various users of the river find a way to reduce average deliveries.

climate change | global warming | hydrology | sustainability | water resources

The Colorado River system provides water to ≈27 million people in the southwest United States and Mexico. As the population of the region grew rapidly in recent decades, ever more water was supplied from the river to support this growth. Today the water is almost totally subscribed.

During this period of rapid growth, the hydrological cycle in the region began to change (1–3). Snowpack declined in the western mountains, temperatures increased, and many streams gradually shifted their peak flow to earlier in the year. It has been shown, with very high statistical confidence ($P < 0.01$), that a substantial portion of these changes are attributable to human-induced effects on the climate (3–6). Those works also show that at least 2 global climate models, downscaled to the western United States and using anthropogenic forcing, explain these changes quite well.

Those same global climate models indicate that the southwestern United States will become warmer and more arid, especially in the Colorado River drainage basin. Temperature increases of 2–4 °C are projected by 2050. The precipitation forecasts are in less agreement, ranging from essentially no change to reductions of ≈10% (2, 7–10). Despite the range of precipitation results, climate models are strikingly consistent in projecting decreased runoff in the Colorado River Basin (Table 1) (2, 8–12). For example, of 12 global models selected to provide the best simulation of historical runoff compared with observations, 11 showed drying in the Upper Colorado River Basin (12). Statistically based studies show the same result (2, 7, 13). The bottom line is that these changes in the climate will likely reduce the flow of the Colorado River by 10–30%.

In earlier work (14), we explored when these human-induced changes in the Colorado River system might exhaust reservoir storage. As we noted in reference 14, water managers will do everything within their power to avoid this drastic scenario. The reservoirs are operated by the United States Bureau of Reclamation (USBR), which will likely cut deliveries as necessary to maintain Lake Mead's elevation above the water intake for Las Vegas and surrounding communities (305 m above mean sea level). Because Lakes Mead and Powell are man-made, minimum elevations are determined by the USBR, and such protection is entirely achievable. However, simply saying this elevation will be protected does not address what such a constraint would entail in terms of reduced water deliveries, when deliveries would start to be affected, or how large the delivery cuts necessary to maintain this elevation would be.

How climate change is likely to alter Colorado River water deliveries has been addressed by a number of studies (2, 7–10, 15). Those works consistently found that the warmer and drier future conditions from human-induced climate change give a substantial chance of reduced river flow and associated water-delivery shortfalls in the 21st century. Here we extend those studies to estimate multiple time series of probabilities of future Colorado River water deliveries and water-delivery shortages. These results provide quantitative information on the size and timing of future delivery shortfalls and were calculated by using both the scheduled increase in water deliveries and the cuts that will be used under shortage conditions (16). We also examine the impact of different estimates of mean Colorado flow on deliveries and shortages, and illustrate the increasing chance that years will exist when only very low water deliveries are possible. This information, embedded in a realistic probabilistic framework, offers real-life numbers on expected river flow and sustainable water deliveries suitable for planning ways to address the coming water shortages in the Colorado Basin.

Colorado River Budget Model (CRBM). We use an updated version of the CRBM, which is a simple water budget model that calculates the net effect of inflows and outflows at a monthly time step. The earlier version (14) attracted a number of criticisms that we have addressed in this revision. In particular, we include the decline in the reservoir evaporation as their surface areas shrink. Also, the "preferred alternative" schedule of delivery cuts adopted by the USBR in 2007 (16) is included in this new model. The deepest delivery cuts specified in this alternative are 0.74 billion cubic meters per year [(bcm/yr); equal

Author contributions: T.P.B. and D.W.P. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed at: Division of Climate, Atmospheric Science, and Physical Oceanography, Mail Stop 0224, Scripps Institution of Oceanography, La Jolla, CA 92093-0224. E-mail: timdotbarnett@ucsd.edu.

This article contains supporting information online at www.pnas.org/cgi/content/full/0812762106/DCSupplemental.

Table 1. Estimates of future decrease in runoff in the Colorado River basin due to human-induced climate change

Source	Runoff reduction
Nash and Gleick (1991)	12–31%†
Nash and Gleick (1993)	8–20%
Christensen et al. (2004)	18%
Milly et al. (2005)	10–25%
Seager et al. (2007)	15–20%
Christensen and Lettenmaier (2007)	6–7%
Hoerling and Eischeid (2007)	45%‡
McCabe and Wolock (2007)	8–17%

†Authors examined a range of values, quoted numbers are for (+2 °C, no change in precipitation) and (+4 °C, −10% precipitation) in the 2-basin model; see original work for details.
‡Estimate under revision.

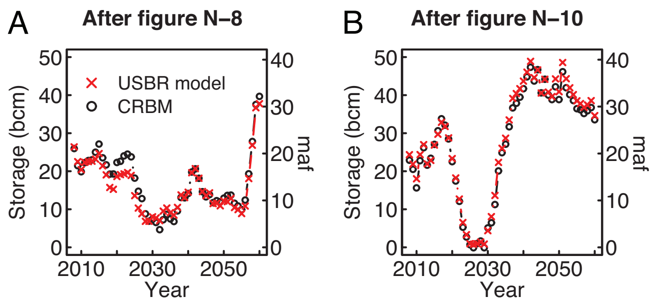


Fig. 1. Model simulations of total active storage in Lakes Mead and Powell for the CRBM model used here (black circles) and the full USBR Colorado River model (red crosses). The 2 inflow sequences and USBR model results (*A*, after figure N-8; *B*, after figure N-10) are taken from ref. 16, appendix N, figures 7–10 with elevations converted to total active storage.

to 0.6 million acre-feet per year (maf/yr)*]. Climate change is taken as starting in 1985, as indicated by observations of temperature, streamflow, and snowpack over the western United States (4). A 305-m (1,000-ft) elevation of Lake Mead—the level of the Southern Nevada Water Authority intake—is protected even if Lake Powell is depleted and water-delivery cuts deeper than those specified in the preferred alternative become necessary to protect this elevation. At this elevation, the reservoirs are only 8% full if Lake Powell is depleted. Other model details are given in the *SI Text*. All model runs start in 1960, so our results are not affected by the unusually low reservoir conditions in 2008 (see also *SI Text*, section S-2, and Fig. S1).

Fig. 1 compares the new version of CRBM with results from USBR's Colorado River Simulation System (CRSS) model (see ref. 16, appendix N, figures 7–10, and Table S1). The average rms error is 1.85 bcm/yr (1.5 maf/yr), which arises primarily from the neglect of the operations of other reservoirs in the system. Sensitivity tests to the imperfectly known flows and losses in the Colorado system show that the uncertainties could shift our results by ±5 years. Otherwise our conclusions remain robust to reasonable perturbations in these numbers.

The model improvements noted in the *SI Text* have a variety of effects. Compared with our earlier work (14), the improved models delay the onset of problems by ≈4–10 years when using the same inflow assumptions, depending on the particular scenario. More details are given in the *SI Text*.

Using CRBM allows us to explore the parameter space that affects future deliveries. Additionally, numerous realizations of future river flows can be computed, all consistent with the statistical properties of the historical Colorado River flow but differing in their exact sequence of yearly values. This ability allows future deliveries to be evaluated probabilistically, which is appropriate because the sequence of future flows is not deterministically predictable. The water budget model therefore serves a different purpose than a slower running, but more complete, model of the Colorado River system, such as the USBR's CRSS model. We believe the combination of information from both types of models will provide the best basis for planning the future of this critical resource.

Impact of Climate Change on Deliveries. Our main purpose is to investigate the effect of climate change on deliveries of water from the Colorado River when protecting a 305-m elevation of Lake Mead, the elevation of the lowest water intake for Southern Nevada. Is it likely that scheduled deliveries can be met in the future, and, if not, what are the shortfalls likely to be and when will they occur?

In this section, we assume that 20th-century naturalized Colorado River flow at Lees Ferry, AZ is representative of future values in the absence of climate change. Because measurements started in 1906 and we take the beginning of climate-change effects to be 1985, we use the mean value from 1906–1984—18.86 bcm/yr (15.30 maf/yr)—as our estimate of Colorado River flow unaffected by climate change. Paleoclimate research suggests this is an overestimate; the effects of using a mean flow consistent with the tree-ring record are significant and are examined below.

We ran the water budget model 100 years into the future, and the water available each year was compared with scheduled deliveries (see ref. 16, appendix C). This process was repeated for 10,000 independent realizations of Colorado River flow. As befits our water budget approach, we compare the total water available to the total demand without regard to how the complex legal rights to the water determine where shortages occur.

Fig. 2 shows the probability of experiencing delivery shortages as a function of time. In the absence of climate change, shortfalls occur ≈40% of the time by midcentury and their magnitude remains modest. However, both the likelihood and size of shortfalls increase rapidly as increasing scheduled deliveries and climate change begin to affect the system. With a 10% reduction in Colorado River runoff, full deliveries are no longer the norm by 2040. With a 20% runoff reduction, delivery shortfalls of >1 bcm/yr (0.81 maf/yr) become more common than full deliveries by 2043. By 2060, shortfalls are experienced 70–95% of the time; the mean annual delivery shortfall is 1.3 bcm/yr (1 maf/yr) if runoff reduces 10% and 2.6 bcm/yr (2 maf/yr) if runoff reduces 20%. These values are ≈1.5- to 3-times the maximum lower basin delivery cut explicitly included in the preferred alternative plan.

Mean shortfalls, also discussed in earlier work (2, 7–10), do not tell the whole story. The large number of realizations in CRBM and its statistical framework allowed us to look at extremes in expected shortages. The results show that if absolute protection of the 305-m elevation in Lake Mead is desired, delivery cuts of >2.5 bcm/yr (2 maf/yr) are sometimes required under climate-change scenarios. We note that a USBR simulation driven by a flow with 20% reduced mean, which would be unremarkable if climate changes reduce runoff 20%, was unable to protect the 305-m elevation of Lake Mead even with cuts up to 4.1 bcm/yr (3.3 maf/yr) (see ref. 16, p. N-18).

Low-flow years when protection of the Lake Mead elevation requires delivery of less than, say, 14.5 bcm (11.75 maf) from a request of ≈17.3 bcm (14 maf) would require substantial accommodation by the users. The fraction of time cuts of this magnitude is required to protect the 305-m, elevation and is

*We additionally supply values in the units used in all the USBR documents pertaining to the reservoirs. 1 bcm = 0.81 maf.

SUSTAINABILITY SCIENCE

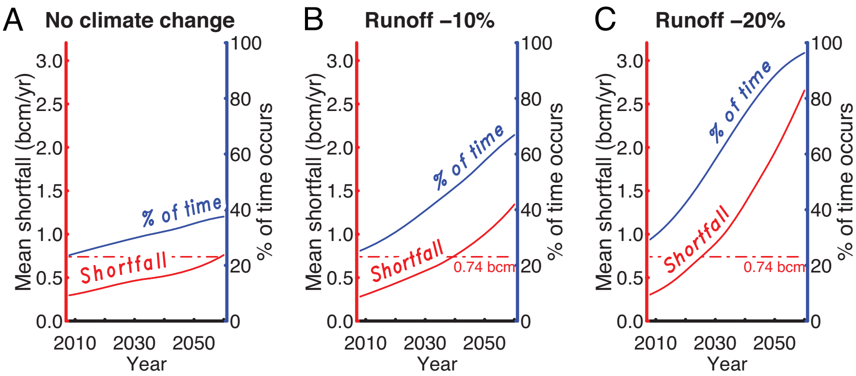


Fig. 2. Probability of experiencing delivery shortages (blue, %), and the mean delivery shortage (red, bcm/yr), for the cases with no climate change (*A*) and a reduction in Colorado River runoff of 10% (*B*) and 20% (*C*). Also shown for comparison is the largest lower-basin delivery cut included in the USBR's preferred alternative of reservoir operations, 0.74 bcm/yr, or 0.6 maf/yr (dashed line).

shown in Fig. 3*A*. There is a negligible chance of such substantial delivery shortages if there is no climate change. With 10% and 20% reductions in runoff, this chance increases to 5% and 21%, respectively, by the middle of this century.

The temporal autocorrelation of the Colorado River flow and intermittent nature of the El Niño/Southern Oscillation cycle gives rise to a dynamic where water is plentiful during infrequent heavy-precipitation years and the Colorado's reservoirs fill. Then the levels slowly decline during subsequent dry years. Fig. 3*B* shows the chance that the reservoirs are at least 80% full. Although this situation was quite likely in the 1980s ($P > 0.8$), it becomes less likely in the future (even without climate change) as increasing deliveries cause the lake elevations to be systematically lowered. With climate change included, the probability of having the reservoirs 80% full falls sharply between 2000 and 2030, with a <10% chance after 2030 if the runoff is reduced by 20%. Intermittent wet years are unable to replenish the reservoirs given climate change and planned future water deliveries.

Sustainable Future Deliveries. Our results indicate that currently scheduled future deliveries are unlikely to be consistently met if the climate changes as projected. Just how much water can the Colorado River sustainably deliver in the face of climate-induced flow reductions? This question does not seem to have been addressed by previous workers.

In Fig. 4, the line marked "D" is the mean water delivered across all model realizations and can be thought of as an upper limit for sustainable water deliveries from the Colorado River. The line marked "B10%" shows the mean of the bottom 10% of deliveries. Also shown, for comparison, are requests for delivery, indicated by the line marked "R." With any climate change that tends toward dryness, the sustainable amount of water the river can provide decreases with time, and the shortfall during low-delivery years becomes more severe.

Using assumed 20th-century flows (Fig. 4 *A–C*), a 10% reduction in runoff caused by human-induced climate change means that requested deliveries exceed sustainable deliveries by 2040. With a 20% reduction in runoff, these shortfalls happen by 2025.

The bottom decile of deliveries has a mean of 14.2 bcm/yr (11.5 maf/yr) by 2050 for a 10% decrease in runoff. With a 20% decrease in runoff, the bottom decile mean is 10.4 bcm/yr (8.4 maf/yr) by 2050. In other words, the greatest effects of climate change will most likely be seen at the delivery extremes, not at the mean.

The occurrence of low-delivery years is partly a consequence of attempting to deliver more water from the Colorado River than it can sustainably supply. Doing so means the reservoirs spend more time in a depleted state, which decreases the buffering ability of the system to maintain deliveries in low-precipitation years. Reducing requested deliveries to be in line with what the river can sustain increases the amount of water delivered in the bottom decile of years because the reservoirs are then maintained at consistently higher elevations. For example, when scheduled depletions are linearly reduced from the current value in 2008 to 14.8 bcm/yr (12 maf/yr) in 2060, the average amount delivered in the bottom decile stays above 12.3 bcm/yr (10 maf/yr) even if runoff declines 20%.

Impact of Paleoclimate Flows on Sustainable Deliveries. We have used 20th-century flows in obtaining the results shown above. However, tree-ring reconstructions of Lees Ferry flow show this was a wet period with unusually high flows in the Colorado River (17–21). Of the 10 reconstructions we examined, 9 show the 20th century as being the wettest of the last 500–1,200 years with the exception showing it as the second wettest over the same timeframe (Fig. 5) (see also *SI Text*, section S-3, and Fig. S2). The bottom line is that using 20th-century flows for evaluating the Colorado River's ability to meet future deliveries is neither a conservative assumption nor one supported by paleoclimate evidence.

Sustainable deliveries that are possible from the system using the average of the 10 paleoclimate flow estimates, 17.38 bcm/yr (14.08 maf/yr), are shown in Fig. 4 *D–F*. A reversion to average climate conditions indicated by the tree-ring records would reduce sustainable deliveries to near the value being requested today, even without anthropogenic climate change (Fig. 4*D*). There is a particularly strong effect on the lowest decile of water deliveries. Calculated using the mean paleoclimate flow, a 10%

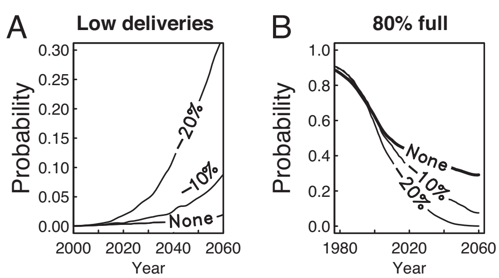


Fig. 3. Probability of delivering <14.5 bcm (11.75 maf) of water in the indicated year (*A*) and probability of the reservoirs being at least 80% full (*B*). Lines show cases with no anthropogenic climate change and with reductions in runoff of 10% and 20% driven by anthropogenic climate change.

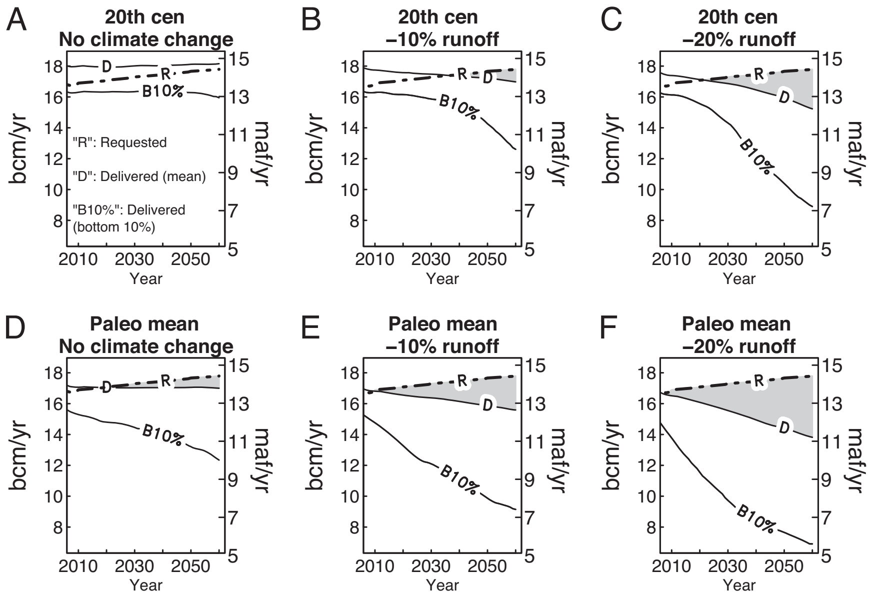


Fig. 4. Mean water deliveries from the Colorado River system under various climate scenarios. Line D shows the mean water delivered across all model realizations and can be thought of as the upper limit of sustainable water deliveries. Line B10% shows mean water delivered during years that fall within the bottom 10% of deliveries. For comparison, line R shows requests for scheduled deliveries. (*A–C*) Computations with 20th-century values of Colorado River flow. (*D–F*) Computations using an assumed Colorado River flow of 17.38 bcm/yr (14.08 maf/yr) at Lees Ferry, AZ, the mean of estimates from 10 different tree-ring reconstructions. Wherever the D line drops below the R line (shaded regions), requests for water are exceeding sustainable deliveries.

reduction in runoff gives a bottom decile mean of ≈10 bcm/yr (8 maf/yr) by 2050. The bottom decile mean drops to 8 bcm/yr (6.5 maf/yr) if anthropogenic forcing reduces runoff by 20%, less than half of the water used today (Fig. S3). As before, reducing scheduled deliveries would increase these numbers and the resiliency of the system.

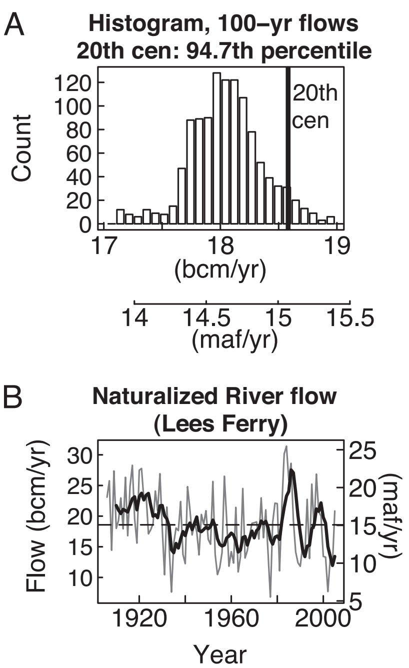


Fig. 5. Historical and Paleoclimate estimates of Colorado River flow. (*A*) Vertical line shows observed (naturalized) mean flow in the Colorado River at Lees Ferry, AZ from 1906–2005 compared with a histogram of the mean flow in all sliding 100-yr segments from a tree-ring-based reconstruction of Colorado River flow (21). (*B*) Time series of naturalized mean annual flow in the Colorado River at Lees Ferry, AZ, along with the 5-year running mean (heavy line) and mean over the period 1906–2005 (18.6 bcm/yr or 15.07 maf/yr) (dashed line).

Discussion and Conclusions

We find that either protecting a 305-m (1,000-ft) elevation in Lake Mead in the face of human-induced climate change or the Colorado River flow reverting back to the lower mean value indicated by tree-ring data, or both, makes it increasingly unlikely that currently scheduled future deliveries can be sustained. In fact, attempting to meet scheduled deliveries increases the number of years where the only deliveries possible are <14.5 bcm/yr (11.75 maf/yr) of the requested ≈17.3 bcm/yr (14 maf/yr).

The difficult situation described above could be ameliorated by aiming for more realistic deliveries that are lower than those currently scheduled. We have shown that lower delivery requests would reduce the likelihood of having years in which the only option available is to deliver <14.5 bcm/yr of water (assuming the 305-m elevation of Lake Mead is protected).

In any event, currently scheduled water deliveries from the Colorado system are not sustainable in the future if anthropogenic climate change reduces runoff even by as little as 10%. If Colorado River flow reverts to the long-term mean suggested by tree-ring studies, currently scheduled deliveries cannot be met even in the absence of runoff reductions due to anthropogenic climate change.

This work adds to and strengthens our previous results (14) as well as those from other workers (2, 7–10). The Colorado River faces scheduled increases in water delivery combined with the likelihood of reduced runoff caused by climate change in a system conceived during and calibrated to one of the wettest centuries in the last 1,200 years. Lake Mead has been overdrafted by an average of 1.6 bcm/yr (1.3 maf/yr) since 1999 (22). Colorado River delivery shortfalls could become systematic if current delivery schedules are followed and river management guidelines are unchanged.

Our results suggest long-term sustainable deliveries from the Colorado River are likely in the range of 14–17 bcm/yr (11–13.5

SUSTAINABILITY SCIENCE

maf/yr). These numbers represent a reduction of 0–20% relative to current deliveries. Those are potentially substantial shortfalls but are likely manageable through a program of water reuse, conservation, transfers between users, and other measures (15).

The situation becomes more complicated when future deliveries to support population and economic growth in the region are taken into account. The upper basin states have long-standing plans to increase their depletions to support such growth in accord with established agreements on division of the water and as reflected in the USBR delivery schedules used in this work. Although it has been known for many decades that the Colorado River water was originally overallocated and that this problem would have to be addressed eventually, our results show this is no longer a problem for future generations to debate. The problem is at our threshold and appears solvable, at least in the near term. But it needs to be addressed now. The USBR Interim Agreement was a good first step, but neglect of climate-change effects means that it is working from overly optimistic assumptions. Hopefully, information such as that developed here will provide a basis for those managing water resources in the flexible way needed to cope with less water in the future.

We wish to end with a caveat. The effects associated with a reversion of the Colorado River flow to its paleoclimate mean impart a substantial uncertainty into the magnitude and timing of the delivery problems. Beyond some consensus regarding what to use as a realistically conservative (low) mean flow, we need a scheme to predict the river flow at ten- to twenty-year time scales. A combination of global climate models, downscaling, and hydrological models in a proper statistical framework has already been used to demonstrate how such forecasts can be made (9, 10, 23). We suggest it would be prudent to implement operationally such a forecast system for the Colorado Basin as soon as possible.

ACKNOWLEDGMENTS. We thank Dr. Niklas Christensen, Dr. Hugo Hidalgo, and Dr. Dennis Lettenmaier for comments on the manuscript. We would also like to thank the United States Bureau of Reclamation personnel who supplied some of the data used in this study, the University of California at San Diego Supercomputing Center, and the Scripps Institution of Oceanography where work was done. This work was supported by Livermore-UC San Diego Scientific Data, a joint program between the University of California at San Diego and Lawrence Livermore Research Lab.

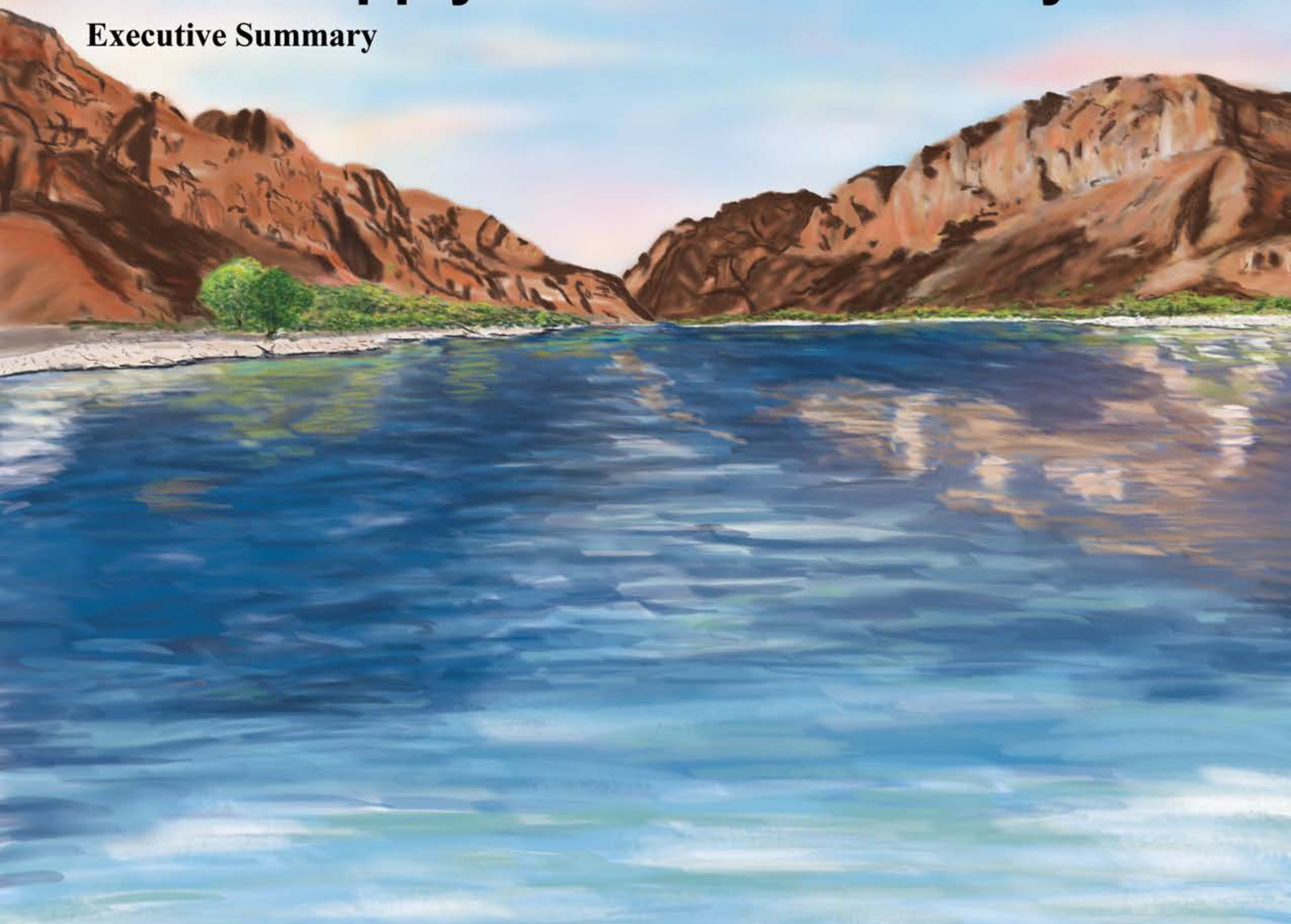
1. Mote PW, Hamlet AF, Clark MP, Lettenmaier DP (2005) Declining mountain snowpack in western North America. *Bull Am Meteorol Soc* 86:39–49.
2. Nash LL, Gleick PH (1991) Sensitivity of stream flow in the Colorado basin to climate change. *J Hydrol* 125:221–241.
3. Bonfils C, et al. (2008) Detection and attribution of temperature changes in the mountainous western United States. *J Climate* 21:6404–6424.
4. Barnett TP, et al. (2008) Human-induced changes in the hydrology of the western United States. *Science* 319:1080–1083.
5. Pierce DW, et al. (2008) Attribution of declining western U.S. snowpack to human effects. *J Climate* 21:6425–6444.
6. Hidalgo HG, et al. (January 26, 2009) Detection and attribution of streamflow timing changes to climate change in the western United States. *J Climate*, 10.1175/2009JCLI2470.1.
7. McCabe GJ, Wolock DM (2007) Warming may create substantial water supply shortages in the Colorado River basin. *Geophys Res Lett* 10.1029/2007GL031764.
8. Nash L, Gleick P (1993) The Colorado Basin and climate change. EPA, Policy, Planning and Evaluation, EPA Publ No 230-R-93–009.
9. Christensen NS, Wood AW, Voisin N, Lettenmaier DP, Palmer RN (2004) Effects of climate change on the hydrology and water resources of the Colorado basin. *Climatic Change* 62:337–363.
10. Christensen NS, Lettenmaier DP (2007) A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrol Earth Syst Sci* 11:1417–1434.
11. Seager R, et al. (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184.
12. Milly P, Dunne K, Vecchia A (2005) Global pattern of trends in streamflow and water availability in a changing climate. *Nature* 438:347–350.
13. Hoerling M, Eischeid J (2007) Past peak water in the Southwest. *Southwest Hydrol* 35:18–19.
14. Barnett TP, Pierce DW (2008) When will Lake Mead go dry? *Water Resour Res*, 10.1029/2007WR006704.
15. Committee on the Scientific Basis of Colorado Basin River Water Management, National Research Council (2007) *Colorado River Basin Management: Evaluating and Adjusting to Hydroclimatic Variability*. (National Academies, Washington, D.C.).
16. U.S. Bureau of Reclamation (2007) *Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*. Available online at: www.usbr.gov/lc/region/programs/strategies/FEIS/index.html. Accessed Nov 14, 2007.
17. Stockton CW, Jacoby GC, Jr. (1976) Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin based on tree-ring analysis. *Lake Powell Research Project Bulletin* (Institute of Geophysics and Planetary Physics, Univ of California, Los Angeles), No. 18.
18. Michaelsen JH, Loaiciga A, Haston L, Garver S (1990) *Estimating Drought Probabilities in California Using Tree Rings. California Department of Water Resour Report B-57105*. (Univ of California, Santa Barbara, CA).
19. Hidalgo HG, Piechota TC, Dracup JA (2000) Alternative principal components regression procedures for dendrohydrologic reconstructions. *Water Resour Res* 36:3241–3249.
20. Woodhouse CA, Gray ST, Meko DM (2006) Updated streamflow reconstructions for the Upper Colorado River basin. *Water Resour Res*, 10.1029/2005WR004455.
21. Meko DM, et al. (2007) Medieval drought in the upper Colorado River basin. *Geophys Res Lett*, 10.1029/2007GL029988.
22. U.S. Bureau of Reclamation (2006) *Two-Year Projected Reservoir Operations (24-Month Study)*. Available online at www.usbr.gov/lc/riverops.html. Accessed December 5, 2008.
23. Barnett TP, et al. (2004) The effects of climate change on water resources in the west: Introduction and overview. *Climatic Change* 62:1–11.

RECLAMATION

Managing Water in the West

Colorado River Basin Water Supply and Demand Study

Executive Summary



U.S. Department of the Interior
Bureau of Reclamation

December 2012

Mission Statements

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.

Colorado River Basin
Water Supply and Demand Study
Executive Summary

U.S. Department of the Interior
Bureau of Reclamation

December 2012

Reclamation. 2017.Colorado River Basin Water Supply and Demand Study. Executive Summary.

Foreword

The Colorado River is the lifeblood of the southwestern United States. Stretching from the highest peaks of the Rocky Mountains to the Gulf of California, it travels over 1,400 miles across a watershed that includes seven states within the United States and two states in northern Mexico. Nearly 40 million Americans rely on the Colorado River system for drinking water and to support livelihoods ranging from farming to recreation. Emphasizing the economic, cultural, and ecologic significance of this river, our commitment to sound management for generations to come is steadfast. At the forefront of that pledge is the SECURE Water Act, the WaterSMART program, and Basin Studies across the West. These programs elevate water planning and management to new levels with expanded science, collaboration, and forward thinking. Just as we benefit from the planning and works of prior generations, it is our obligation to use the best information available to us to prepare for the water management challenges ahead.

Conducted under the Basin Study Program, the Colorado River Basin Water Supply and Demand Study is the most comprehensive long-term assessment to date of the Colorado River Basin and its invaluable resources. Findings indicate that in the absence of timely action to ensure sustainability, there exists a strong potential for significant imbalances between water supply and demand in coming decades. Through the Study process, a common technical foundation was established, upon which continued dialogue will be built towards actions that will enhance and preserve the future of communities, economies, and ecosystems supported by the Colorado River.

As the Basin copes with yet another year in an unprecedented drought extending back to 1999, the challenges of the task at hand are more real than ever. Though these challenges are unprecedented, I am confident that the partnerships forged and strengthened during this Study and over the years will rise to meet the undertaking with vigor.

Michael L. Connor,
Commissioner, Bureau of Reclamation

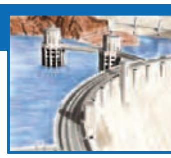
Reclamation. 2017.Colorado River Basin Water Supply and Demand Study. Executive Summary.




Contents

Reclamation. 2017.Colorado River Basin Water Supply and Demand Study. Executive Summary.

FIGURE 1
The Study Area - the hydrologic boundaries of the Basin within the United States, plus the adjacent areas of the Basin States that receive Colorado River water



Executive Summary

Spanning parts of the seven states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming (Basin States), the Colorado River Basin (Basin) is one of the most critical sources of water in the West. The Colorado River and its tributaries provide water to nearly 40 million people for municipal use, supply water to irrigate nearly 5.5 million acres of land, and is the lifeblood for at least 22 federally recognized tribes (tribes), 7 National Wildlife Refuges, 4 National Recreation Areas, and 11 National Parks. Hydropower facilities along the Colorado River provide more than 4,200 megawatts of electrical generating capacity, helping to meet the power needs of the West and offset the use of fossil fuels. The Colorado River is also vital to the United Mexican States (Mexico) to meet both agricultural and municipal water needs.

The Colorado River system is operated in accordance with the Law of the River[1]. Apportioned water in the Basin exceeds the approximate 100-year record (1906 through 2011) Basin-wide average long-term historical natural flow[2] of about 16.4 million acre-feet (maf). However, the Upper Basin States have not fully developed use of their 7.5-maf apportionment, and total consumptive use[3] and loss in the Basin has averaged approximately 15.3[4] maf over the last 10 years. Because of the Colorado River system's ability to store approximately 60 maf, or nearly 4 years of average natural flow of the river, all requested deliveries were met in the Lower Basin despite recently experiencing the worst 11-year drought in the last century. However, there have been periodic shortages throughout the Upper Basin and the adjacent areas of the Basin States that receive Colorado River water.

Lake Mead during drought conditions

1 The treaties, compacts, decrees, statutes, regulations, contracts and other legal documents and agreements applicable to the allocation, appropriation, development, exportation and management of the waters of the Colorado River Basin are often collectively referred to as the Law of the River. There is no single, universally agreed upon definition of the Law of the River, but it is useful as a shorthand reference to describe this longstanding and complex body of legal agreements governing the Colorado River.

2 Natural flow represents the flow that would have occurred at the location had depletions and reservoir regulation not been present upstream of that location.

3 Consumptive use is defined as water used, diminishing the available supply.

4 Basin-wide consumptive use and losses estimated over the period 2002-2011, including the 1944 Treaty delivery to Mexico, reservoir evaporation, and other losses due to native vegetation and operational inefficiencies.

The challenges and complexities of ensuring a sustainable water supply and meeting future demand in an over-allocated and highly variable system such as the Colorado River have been recognized and documented in several studies conducted by the Bureau of Reclamation (Reclamation) and the Basin States over the past several decades. Looking ahead, concerns regarding the reliability of the Colorado River system to meet future Basin resource[5] needs are even more apparent, given the likelihood of increasing demand for water throughout the Basin coupled with projections of reduced supply due to climate change.

The Colorado River and its tributaries provide water to nearly 40 million people for municipal use, supply water to irrigate nearly 5.5 million acres of land, and is the lifeblood for at least 22 federally recognized tribes, 7 National Wildlife Refuges, 4 National Recreation Areas, and 11 National Parks.

It was against this backdrop that the Colorado River Basin Water Supply and Demand Study (Study) was conducted. Funded by Reclamation through the Basin Study Program under the Department of the Interior's WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program and the agencies[6] representing the Basin States, the Study was conducted by Reclamation's Upper Colorado and Lower Colorado Regions and the representatives of the Basin States' agencies. The purpose of the Study was to define current and future imbalances in water supply and demand in the Basin and the adjacent areas of the Basin States that receive Colorado River water over the next 50 years (through 2060), and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. The Study did not result in a decision as to

Green River in Utah

[5] Resources include water allocations and deliveries for municipal, industrial, and agricultural use; hydroelectric power generation; recreation; fish, wildlife, and their habitats (including candidate, threatened, and endangered species); water quality including salinity; flow- and water-dependent ecological systems; and flood control.

[6] The non-Federal cost-share partners are: Arizona Department of Water Resources, the (California) Six Agency Committee, Colorado Water Conservation Board, the New Mexico Interstate Stream Commission, the Southern Nevada Water Authority, the Utah Division of Water Resources, and the Wyoming State Engineer's Office.

how future imbalances should or will be addressed. Rather, the Study provides a common technical foundation that frames the range of potential imbalances that may be faced in the future and the range of solutions that could be considered to resolve those imbalances.

The Study Area is shown in figure 1 and is defined as the hydrologic boundaries of the Basin within the United States, plus the adjacent areas of the Basin States that receive Colorado River water. In many adjacent areas, the Colorado River supply is in addition to other water supply sources used to meet water demands.

The Study was conducted in collaboration with stakeholders throughout the Basin. Interest in the Study was broad, and stakeholders included tribes, agricultural users, purveyors of municipal and industrial (M&I) water, power users, and conservation and recreation groups. Through extensive outreach efforts, the interested parties were engaged and their input was considered. This broad participation and input was critical to the Study.

Because of the inherent complexities of the Study and the many diverse interests and perspectives, eight interim reports and technical updates were published to reflect technical developments and the ongoing input of stakeholders. The final documentation for the Study is organized into three major parts: this *Executive Summary,* a *Study Report*, and seven Technical Reports. A compact disc containing the Study documents in their entirety can be found inside the back cover of the printed report.

Project participants and stakeholders are encouraged to comment on the information provided in the *Study Report* and associated Technical Reports. Comments received before April 19, 2013, will be summarized and posted to the Study website and may inform future planning activities in the Basin. Instructions for submitting comments are also provided on the Study website at: http://www.usbr.gov/lc/region/programs/crbstudy.html.

Recreation boating on Lake Powell in Utah

1.0 Projected Future Water Supply and Demand Scenarios

The amount of water available and changes in the demand for water throughout the Basin over the next 50 years are highly uncertain and depend on a number of factors. The potential impacts of future climate change and variability further contribute to these uncertainties. Nevertheless, projections of future water supply and demand were needed to assess the reliability of the Colorado River system to meet Basin resource needs and to identify options and strategies to mitigate future risks to those resources. To be beneficial, these projections had to be sufficiently broad to capture the plausible ranges of uncertainty in future water supply and demand. A scenario planning process was used to guide the development of scenarios that provided a broad range of projections, resulting in four scenarios related to future water supply and six scenarios related to future water demand.

1.1 Water Supply Scenarios

Since 2004, Reclamation has conducted a multi-faceted research and development programs to investigate and implement a variety of methods for projecting future streamflow for Colorado River planning studies. Based on this work and the information gathered in the scenario planning process, four water supply scenarios were quantified and analyzed. These scenarios are titled Observed Resampled, Paleo Resampled, Paleo Conditioned, and Downscaled General Circulation Model (GCM) Projected and are described as:

- **Observed Resampled:** Future hydrologic trends and variability are similar to the past approximately100 years.

- **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.

- **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:** Future climate will continue to warm with regional precipitation and temperature trends represented through an ensemble of 112 future downscaled GCM projections.

Under the Downscaled GCM Projected scenario, the median of the mean natural flow at Lees Ferry over the next 50 years is projected to decrease by approximately nine percent, along with a projected increase in both drought frequency and duration as compared to the observed historical and paleo-based scenarios. The range of this result varies amongst the individual GCM projections that comprise this scenario with some of the GCM projections showing a larger decrease in mean natural flow than nine percent while others showing an increase over the observed historical mean. Droughts[7] lasting 5 or more years are projected to occur 50 percent of the time over the next 50 years. Projected changes in climate and hydrologic processes include continued warming across the Basin, a trend towards drying (although precipitation patterns continue to be spatially and temporally complex), increased evapotranspiration, and decreased snowpack as a higher percentage of precipitation falls as rain, rather than snow and warmer temperatures, causes earlier melt.

The process of using GCM projections and hydrologic modeling to generate projections of future streamflow presents a number of uncertainties and reflects methodological choices made in the Study. For example, choices of different downscaling techniques or the selection of a different hydrologic model to determine streamflow would yield different results. Notwithstanding minor methodological and reporting differences, the results presented in this report are consistent with Reclamation's report to Congress published in March 2011[8] in fulfillment of the requirements within Section (§) 9503 of the SECURE Water Subtitle of the Omnibus Public Land Management Act of 2009 (Public Law 111-11).

Lees Ferry, Colorado River, Arizona

1.2 Water Demand Scenarios

Historically, Reclamation has considered a single projection of future demands in long-term Basin planning studies. The Study considered a range of projections of demand,

[7] For the purpose of the Study, a drought period occurs whenever the running 2-year average flow at Lees Ferry falls below 15.0 maf, the observed historical long-term mean.

[8] Bureau of Reclamation, 2011. SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011.

developed through a scenario planning process, which is a significant and important advancement in long-term water planning in the Basin. These demands were based on data and information provided by the Basin States, tribes, federal agencies, and other water entitlement holders. Through the scenario planning process, the most critical uncertainties affecting future demand were identified (for example, changes in population and water use efficiency) and were combined into six scenarios, as follows: Current Projected (A), Slow Growth (B), Rapid Growth (C1 and C2), and Enhanced Environment (D1 and D2).

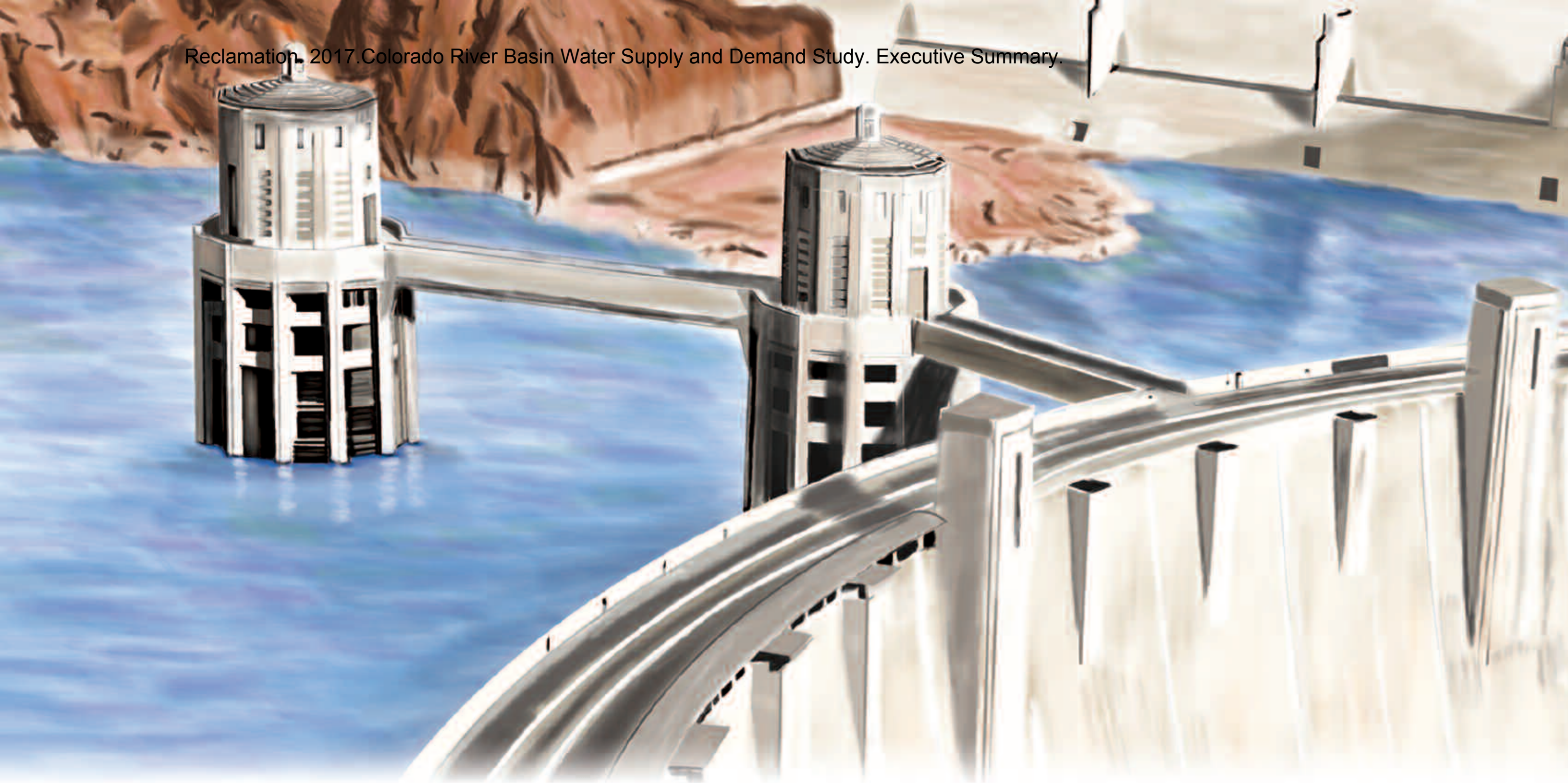
Agricultural irrigation in Arizona

Based on these scenarios, and factoring in both Mexico's 1944 Treaty allotment and water loss due to evaporation and operations, the Colorado River demand for consumptive uses is projected to range between about 18.1 maf under the Slow Growth (B) scenario and about 20.4 maf under the Rapid Growth (C1) scenario by 2060. The largest increase in demand is projected to be in the M&I category, due to population growth. Population within the Study Area is projected to increase from about 40 million in 2015 to between 49.3 million under the Slow Growth (B) scenario and 76.5 million under the Rapid Growth (C1) scenario by 2060. Additionally, the water demand assessment confirmed that the Lower Division States have demand for Colorado River water beyond their 7.5 maf basic apportionment across all scenarios.

The Study considered a range of projections of demand, developed through a scenario planning process, which is a significant and important advancement in long-term water planning in the Basin.

Non-consumptive[9] demands, such as those associated with uses for hydropower and recreation and ecological resources, were included through the development of system reliability metrics and were not quantified in the same manner as demand for consumptive uses. For example, non-consumptive flow targets supporting the environment and recreational activities were developed for several locations throughout the Basin. The impact on these resources was assessed across all combinations of supply and demand scenarios in the Study's system reliability analysis.

9 Non-consumptive use is defined as water used without diminishing available supply.



2.0 Projected Future Water Supply and Demand Imbalances

The range of the projected future water supply and demand in the Basin, as determined through the scenario process, is shown conceptually in figure 2. Without additional future water management actions, a wide range of future imbalances is plausible primarily due to the uncertainty in future water supply. Comparing the median of water supply projections against the median of the water demand projections (medians are indicated by the darker shading), the long-term projected imbalance in future supply and demand is about 3.2 maf by 2060. The imbalance, however, can be much greater (or less) under any one of the multiple plausible future supply and demand scenarios. The projected imbalance in figure 2 does not consider the effect of reservoir storage, which has and will continue to be used to meet Basin resource needs when demand exceeds supply. The potential impacts associated with these imbalances to Basin resources were assessed through modeling and use of system reliability metrics, which consider the effects of reservoir storage.

Dry dock at Lake Mead in Nevada

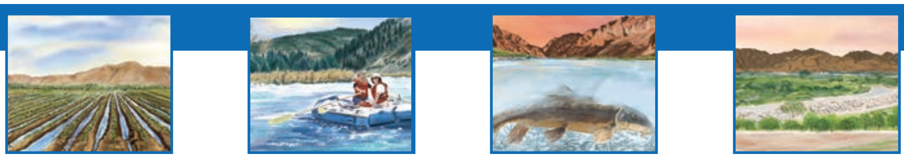
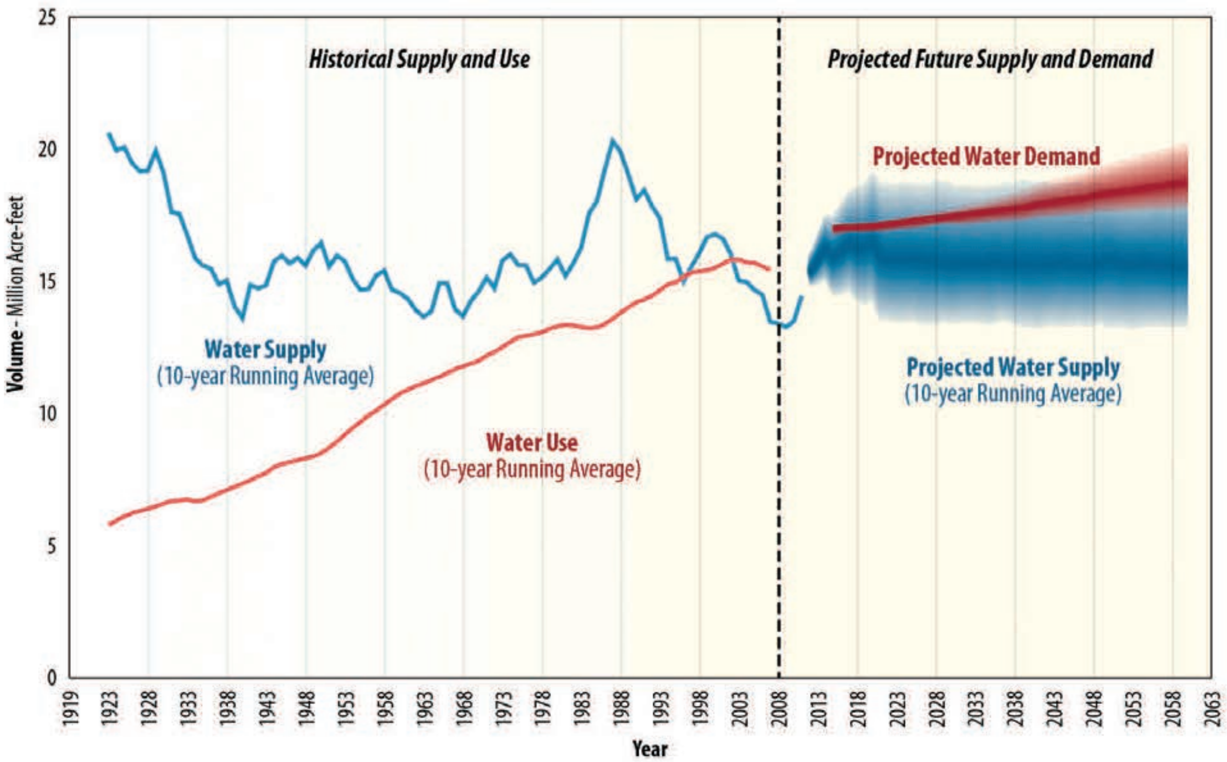


FIGURE 2

Historical Supply and Use[1] and Projected Future Colorado River Basin Water Supply and Demand



[1] Water use and demand include Mexico's allotment and losses such as those due to reservoir evaporation, native vegetation, and operational inefficiencies.

3.0 Options and Strategies to Resolve Supply and Demand Imbalances

The Basin States have made significant investments in developing other water resources and implementing programs and policies to balance current and future supplies with existing and future demands. Many of these efforts have resulted in solutions to past water management challenges and will continue to provide benefit to the system in meeting the challenges that lie ahead.

To identify a broad range of additional potential options to resolve water supply and demand imbalances, input from Study participants, interested stakeholders, and the general public was solicited for consideration in the Study. The solicitation period was from November 2011 through February 2012, and those interested in submitting ideas were asked to complete and submit an option submittal form. During this period, over 150 options were received and were organized into 4 groups: 1) those that increase Basin water supply (Increase Supply), 2) those that reduce Basin water demand (Reduce Demand), 3) those that focus on modifying operations (Modify Operations), and 4) those that focus primarily on Basin governance and mechanisms to facilitate option implementation (Governance and Implementation). Despite the submission of several options that may ultimately be considered too costly or technically infeasible, the Study explored a wide range of options with the goal of ensuring that all viable options were considered.

From these broad groups, categories of options were developed, and each submitted option was assigned to one category based on its primary function. Recognizing that every option submitted could not undergo further evaluation due to time and resource constraints, representative options that spanned the range of the option categories were developed. About 30 representative options were developed to ensure the concepts embodied in each submitted option were reflected and were further evaluated. Many of the representative options were evaluated quantitatively, which entailed an assessment of cost, yield, and timing in addition to assignment of a rating (“A” through “E”) to 14 other criteria, listed in table 1.

TABLE 1
Criteria Used to Evaluate Representative Options

<table>
<tr><th>Technical</th><th colspan="2">Environmental</th></tr>
<tr><td>Technical Feasibility
Implementation Risks
Long-Term Viability
Operational Flexibility</td><td colspan="2">Permitting
Energy Needs
Energy Source
Other Environmental Factors</td></tr>
<tr><th>Social</th><th colspan="2">Other</th></tr>
<tr><td>Recreation
Policy
Legal
Socioeconomics</td><td>Quantity of Yield
Timing
Cost</td><td>Hydropower
Water Quality</td></tr>
</table>

While many of the criteria were assigned a qualitative rating, the assessment of cost, quantity of yield, and timing entailed numeric estimates to facilitate the grouping of these options into portfolios and the modeling of those portfolios. Costs were computed as present day annualized capital, operating, and replacement cost per acre-foot of option yield.

Yuma Desalting Plant, Arizona

It should be noted that the assessment of these criteria was at an appraisal level and there are many associated uncertainties, especially with respect to estimates regarding costs and quantity of yield. A qualitative description was provided for representative options for which the criteria listed in table 1 were not suitable, such as those options in the Governance and Implementation group. A summary of the representative options within the Increase Supply, Reduce Demand, and Modify Operations groups and the cost, yield, and timing, and their inclusion in portfolios, where applicable, is provided in table 2.

The Governance and Implementation group consists of ideas and suggestions related to three major categories: Water Management and Allocation, Tribal Water, and Data and Information. Most concepts related to Water Management and Allocation and Tribal Water have significant legal and policy

TABLE 2

Summary of Representative Options Including Cost, Timing, Potential Yield, and Inclusion in Portfolios

Option Type	Option Category	Representative Option	Estimated Cost ($/afy)	Years before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)	Option Included in Portfolio
Increase Supply	Desalination	Gulf of California	2,100	20 - 30	200,000	1,200,000	Portfolios A, B (up to 400 kafy)
		Pacific Ocean in California	1,850-2,100	20 - 25	200,000	600,000	Portfolios A, B (up to 400 kafy)
		Pacific Ocean in Mexico	1,500	15	56,000	56,000	Portfolios A, B
		Salton Sea Drainwater	1,000	15 - 25	200,000	500,000	All Portfolios
		Groundwater in Southern California	750	10	20,000	20,000	All Portfolios
		Groundwater in the Area near Yuma, Arizona	600	10	100,000	100,000	All Portfolios
		Subtotal			**776,000**	**2,476,000**	
	Reuse	Municipal Wastewater	1,500 - 1,800	10 - 35	200,000	932,000	All Portfolios
		Grey Water	4,200	10	178,000	178,000	Portfolio C
		Industrial Wastewater	2,000	10	40,000	40,000	All Portfolios
		Subtotal			**418,000**	**1,150,000**	
	Local Supply	Treatment of Coal Bed Methane - Produced Water	2,000	10	100,000	100,000	Portfolios A, B
		Rainwater Harvesting	3,150	5	75,000	75,000	Portfolio C
		Subtotal			**175,000**	**175,000**	
	Watershed Management	Brush Control	7,500	15	50,000	50,000	None
		Dust Control	220 - 520	15 - 25	280,000	400,000	Portfolios A, C
		Forest Management	500	20 - 30	200,000	300,000	None
		Tamarisk Control	400	15	30,000	30,000	Portfolios A, C
		Weather Modification	30 - 60	5 - 45	700,000	1,700,000	All Portfolios (up to 300 kafy)
		Subtotal			**1,260,000**	**2,480,000**	
	Importation	Imports to the Colorado Front Range from the Missouri or Mississippi Rivers	1,700 - 2,300	30	0	600,000	Portfolios A, B
		Imports to the Green River from the Bear, Snake [1] or Yellowstone Rivers	700 - 1,900	15	158,000	158,000	None
		Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River [1]	2,700 - 3,400	15	600,000	600,000	None
		Subtotal			**758,000**	**1,358,000**	

TABLE 2

Summary of Representative Options Including Cost, Timing, Potential Yield, and Inclusion in Portfolios

Option Type	Option Category	Representative Option	Estimated Cost ($/afy)	Years before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)	Option Included in Portfolio
Reduce Demand	M&I Water Conservation	M&I Water Conservation	500 - 900	5 - 40	600,000	1,000,000	All Portfolios
		Subtotal			**600,000**	**1,000,000**	
	Agricultural Water Conservation	Agricultural Water Conservation	150 - 750	10 - 15	1,000,000	1,000,000	All Portfolios
		Agricultural Water Conservation with Transfers	250 - 750	5 - 15	1,000,000	1,000,000	All Portfolios
		Subtotal			**1,000,000**[2]	**1,000,000**[2]	
	Energy Water Use Efficiency	Power Plant Conversion to Air Cooling	2,000	10	160,000	160,000	All Portfolios
		Subtotal			**160,000**	**160,000**	
Modify Operations	System Operations	Evaporation Control via Canal Covers	15,000	10	18,000	18,000	None
		Evaporation Control via Reservoir Covers	15,000	20	200,000	200,000	None
		Evaporation Control via Chemical Covers on Canals or Reservoirs	100	15 - 25	200,000	850,000	None
		Modified Reservoir Operations	N/A	15	0 - 300,000	0 - 300,000	None
		Construction of New Storage	2,250	15	20,000	20,000	None
		Subtotal			**588,000**[3]	**1,238,000**[3]	
	Water Transfers, Exchanges, and Banking	Water Transfers and Exchanges (same as Agricultural Water Conservation with Transfers)	250 - 750	5 - 15	1,000,000	1,000,000	All Portfolios
		Upper Basin Water Banking[4]	N/A	10	500,000	800,000	Portfolios A,C
		All Options			**5,735,000**[5]	**11,037,000**[5]	

Table 2 Notes

1 Among the more than 150 options submitted to Reclamation as responsive to the Plan of Study, additional importation of water supplies from various sources, including importation of water from the Snake and Columbia River systems, were submitted to the Study. Such options were appropriately reflected in the Study, but did not undergo additional analysis as part of a regional or river basin plan or any plan for a specific Federal water resource project. The Study is not a regional or river basin plan or proposal or plan for any Federal water resource project.

2 The two agricultural water conservation representative options derive potential yield from similar measures and are thus not additive.

3 Subtotal assumes 150,000 afy for the Modified Reservoir Operations representative option.

4 The values related to Upper Basin Banking reflected assumptions developed for modeling purposes. It was assumed that bank water is generated through conservation; therefore, the potential yield of the bank is consistent with the Upper Basin portion of agricultural and M&I conservation and energy water use efficiency.

5 Total does not account for several options that may be mutually exclusive due to regional integration limitations or are dependent on the same supply.

Glen Canyon Dam, Arizona

considerations and were included in the Study but were not assessed. Where appropriate, these concepts will require future discussions beyond the scope of the Study. Data and Information ideas recommended future data and tool development to support future planning activities in the Basin.

When considering all options and all categories, the potential yield is approximately 5.7 maf per year (mafy) by 2035 and more than 11 mafy by 2060. However, not all options are equally feasible or reliable in the long term. Some options, such as imports into southern California via submarine pipelines, water bags, icebergs, or those related to watershed management (e.g. weather modification or dust control), have either significant technical feasibility challenges or significant questions regarding their reliability. Excluding options that rate low for these factors, the potential yield is reduced to approximately 3.7 mafy by 2035 and to approximately 7 mafy by 2060.

Recognizing no single option will be sufficient to resolve future projected supply and demand imbalances, groups of options, called portfolios, were developed to reflect different adaptive strategies. Each portfolio consists of a unique combination of options that were considered to address Basin resource needs—for example, the water elevation in Lake Mead—that may exist under future combinations of supply and demand. Four portfolios were evaluated in the Study and represent a range of reasonable but different approaches for resolving future supply and demand imbalances. The portfolios are not intended to represent all possible strategies for grouping options. Further, the Study does not result in the selection of a particular portfolio or any one option from any portfolio. The

objective of the portfolio analyses is to demonstrate the effectiveness of different strategies in resolving future supply and demand imbalances.

Using the ratings associated with the criteria listed in table 1 to express certain preferences towards a future strategy resulted in two portfolios, *Portfolio B* and *Portfolio C*. Two other portfolios were then developed, *Portfolio A* and *Portfolio D*, to represent a highly inclusive strategy that includes all options in either *Portfolio B* or *Portfolio C* and a highly selective strategy that includes only options included in both *Portfolio B* and *Portfolio C*. The four portfolios considered in the Study are summarized in table 3.

Portfolio B is based on a strategy that seeks long-term water supply reliability through implementation of options with high technical feasibility and long-term reliability. The strategy can be defined as seeking options with proven technology that, once in place, will produce reliable long-term yield. The strategy represents a low-risk strategy in the long term, but allows greater risk with respect to permitting and implementation.

Conservation landscaping in Arizona

Portfolio C focuses on options that are technically feasible but also may have lower environmental impacts such as low energy needs, lower carbon energy sources, low permitting risk, and low impacts to other environmental factors. The strategy can be defined as one that prioritizes options providing long-term solutions that are flexible and seek to enhance ecological and recreational flows while minimizing the effects on other Basin resources. The strategy represents a low-risk strategy in the near term but allows greater risk with respect to long-term performance of conservation measures.

TABLE 3
Study Portfolios

Portfolio Name	Portfolio Description
Portfolio A	**Is the least restrictive and contains all options that are in both *Portfolio B* and *Portfolio C.***
Portfolio B	**Includes options with high technical feasibility and high long-term reliability; excludes options with high permitting, legal, or policy risks.**
Portfolio C	**Includes only options with relatively low energy intensity; includes an option that results in increased instream flows; excludes options that have low feasibility or high permitting risk.**
Portfolio D	**Is the most selective and contains only those options that are included in both *Portfolio B* and *Portfolio C.***

4.0 Evaluation of Options and Strategies to Resolve Supply and Demand Imbalances

The evaluation of the effectiveness of the four portfolios at resolving future potential supply and demand imbalances consisted of the following: identifying the reliability of the system at meeting Basin resource needs under all future supply and demand scenarios without portfolios in place (termed "Baseline" system reliability); defining of vulnerable conditions—those stressing to Basin resources; and evaluating the effectiveness of portfolios as measured by their ability to improve system reliability and reduce vulnerabilities relative to the Baseline. The estimation of cost and other tradeoffs associated with implementing the four portfolios were also explored.

Southwestern willow flycatcher

The performance of Basin resources was measured through system reliability metrics (metrics). With broad stakeholder involvement, a comprehensive set of metrics that span six resource categories (Water Delivery, Electrical Power, Water Quality, Flood Control, Recreational, and Ecological Resources) was identified. From those metrics, levels reflecting vulnerability or resource risk were identified. The combination of a particular metric and the assumed level of risk are termed "vulnerability." Two important vulnerabilities that provide an overall indication of system reliability are: 1) Lake Mead elevation dropping below 1,000 feet above mean sea level (msl) in any month and 2) Lee Ferry deficit[10], when the 10-year

[10] Article III(d) of the Colorado River Compact stipulates that the Upper Division States will not cause the flow of the river at the Lee Ferry Compact Point to be depleted below an aggregate of 75 maf for any period of 10 consecutive years. For the purpose of the Study, a Lee Ferry deficit is defined as the difference between 75 maf and the 10-year total flow arriving at Lee Ferry.

running total flow at Lee Ferry, Arizona is less than 75 maf.

Baseline system reliability was modeled considering all combinations of the supply and demand scenarios. Additionally, two operational assumptions regarding Lake Powell and Lake Mead operations beyond the effective period of the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operation for Lake Powell and Lake Mead in 2026 were considered. Since each supply scenario has over 100 individual sequences, the Baseline system reliability is comprised of over 20,000 simulations. Despite the findings from the water demand assessment that the Lower Division States have demand for Colorado River water beyond their 7.5 maf basic apportionment, the Baseline system reliability assumes deliveries to the Lower Division States remain consistent with and within their basic apportionment.

In summary, the Baseline analysis indicates that without action, it will become increasingly difficult for the system to meet Basin resource needs over the next 50 years. Future projected development of water supplies and increased consumptive use in the Upper Basin combined with potential reductions in future supply results in reduced volumes of water stored in system reservoirs. With lower water elevations in reservoirs, the needs for resources such as hydropower and shoreline recreation were less frequently satisfied, while water delivery shortages increased. Decreases in flows in key river tributaries have negative implications for flow-dependent resources such as boating recreation and river ecology. These findings fully support the need to develop and evaluate options and strategies to help resolve the water supply and demand imbalance.

Green River below Flaming Gorge Dam, Utah

Vulnerabilities for the latter period of the Study period (2041 through 2060) under Baseline conditions are summarized in table 4.

The Baseline system reliability also reveals that many combinations of future water supply and demand result in management challenges. In fact, most combinations stress some Basin resources through 2060. In the near-term (2012 through 2026), water demands are similar across scenarios, and the largest factor affecting the system reliability is water supply. In the mid-term (2027 through 2040), the demand for water is an increasingly important element in the reliability of the system, as are assumptions regarding the operations of Lakes Powell and Mead. In the long-term (2041 through 2060), the futures that consider the Downscaled GCM Projected water supply scenario, which incorporates projections of future climate, show a high inability to meet resource needs, regardless of the demand scenario and the operation of Lakes Powell and Mead. The first stage in the portfolio analysis revealed that when all options in the most inclusive portfolio *(Portfolio A)* are implemented immediately upon availability, and without meeting demand of the Lower Division States above 7.5 maf, plausible futures still exist in

which the system is vulnerable. While the implementation of these options results in a sizeable reduction in vulnerability (the percentage of futures resulting in Lake Mead elevations being less than 1,000 feet msl is reduced from about 19 percent to 3 percent), these results indicate that complete elimination of Basin vulnerability is not likely attainable.

Because the Lower Division States have demand for Colorado River water above their 7.5 maf basic apportionment, any Basin-wide strategy must take this into consideration. As such, the portfolio analysis was designed to not only implement options to reduce system vulnerability, but also to satisfy the Lower Division States' demand above the 7.5 maf basic apportionment. Augmentation, reuse, and conservation (with and without transfers) were the only options included in the portfolio analysis that could be used to satisfy these demands.

A summary of the system reliability results with the four portfolios in place is also summarized in table 4. Each portfolio was modeled under all future conditions that comprised the Baseline reliability, resulting in

TABLE 4

Summary of System Reliability Outcomes (Percent of Years Vulnerable) for Baseline and Portfolios for All Scenarios, 2041–2060 Period

Resource	System Vulnerability	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Water Delivery	Upper Basin (Lee Ferry Deficit)	**7%**	2%	2%	3%	3%
	Lower Basin (Lake Mead pool elevation below 1,000 feet msl)	**19%**	3%	3%	5%	6%
Electrical Power	Upper Basin Generation (below 4,450 gigawatts per hour per year for 3 consecutive years)	**18%**	9%	10%	10%	11%
	Lower Basin Generation (Lake Mead pool elevation below 1,050 feet msl)	**42%**	14%	14%	19%	20%
Flood Control	Critical River Stage below Hoover Dam (greater than 28,000 cubic feet per second)	**1%**	4%	4%	3%	34%
Water Quality	Salinity below Parker Dam (greater than numeric criteria)[1]	**0%**	0%	0%	0%	0%
Recreation	Colorado River Boating (days less than current conditions with variable hydrology)	**30%**	14%	16%	17%	19%
	Lake Powell Shoreline Facilities (pool elevation less than 3,560 feet msl)	**24%**	11%	11%	12%	13%
	Lake Mead Shoreline Facilities (pool elevation less than 1,080 feet msl)	**57%**	31%	30%	37%	39%
Ecological	Colorado River Flow (less than targeted flow conditions)	**38%**	30%	28%	30%	31%
	Hoover Dam to Davis Dam Flow Reductions (annual flow change greater than 845 thousand acre-feet)	**12%**	4%	4%	7%	8%

[1] The salinity component of the Colorado River Simulation System as presently configured works only with direct observed and paleo-reconstructed data. As such, values reported do not include results from the Paleo Conditioned and the Downscaled GCM Projected scenario.

over 20,000 simulations for each portfolio. The portfolios were modeled such that options were implemented only when needed to address specific vulnerabilities, thus minimizing the investment simulated in the analysis. As shown in the table, inclusion of the portfolios was projected to improve the ability to meet Basin resources needs (i.e. reduce vulnerabilities). The vulnerabilities related to critical Upper Basin and Lower Basin water delivery metrics were reduced by 50 percent or more. The results for metrics related to electrical power, water quality, recreation, and ecological resources indicate similar reductions in vulnerabilities. Only the metric related to flood control below Hoover Dam shows a slight increase in vulnerability due to the potential for higher reservoir storage (and higher likelihood of high release) when portfolios were included.

Although these reductions in vulnerabilities are encouraging, vulnerabilities continue to be present under some conditions, even when every option was implemented as soon as it was assumed to be available. This result is primarily because of the hydrologic conditions driving those vulnerabilities. Statistical analysis was performed to determine the specific hydrologic conditions (e.g., droughts of a particular length) that tended to result in certain critical vulnerabilities (e.g., Lee Ferry deficit and Lake Mead elevation less than 1,000 feet msl). Under Baseline conditions, the potential for these critical vulnerabilities was found to be strongly correlated to long-term mean natural flows at Lees Ferry below the historical average of 15.0 maf and droughts of 8 years or greater in duration.

Although the implementation of the portfolios does not completely eliminate the occurrence of such critical vulnerabilities, the portfolios are successful in significantly improving the resiliency of Basin resources to these vulnerable hydrologic conditions. With portfolios in place, the system is able achieve similar levels of reliability under more adverse hydrologic conditions. Specifically, with portfolios in place, the long-term average flow to which the Basin is vulnerable is about 0.5 mafy less and the magnitude of the 8-year period of lowest flows is increased about 1 mafy. This type of information provides insight into specific hydrologic conditions that the system should be able to successfully endure and can inform water managers when crafting strategies to effectively hedge against those events.

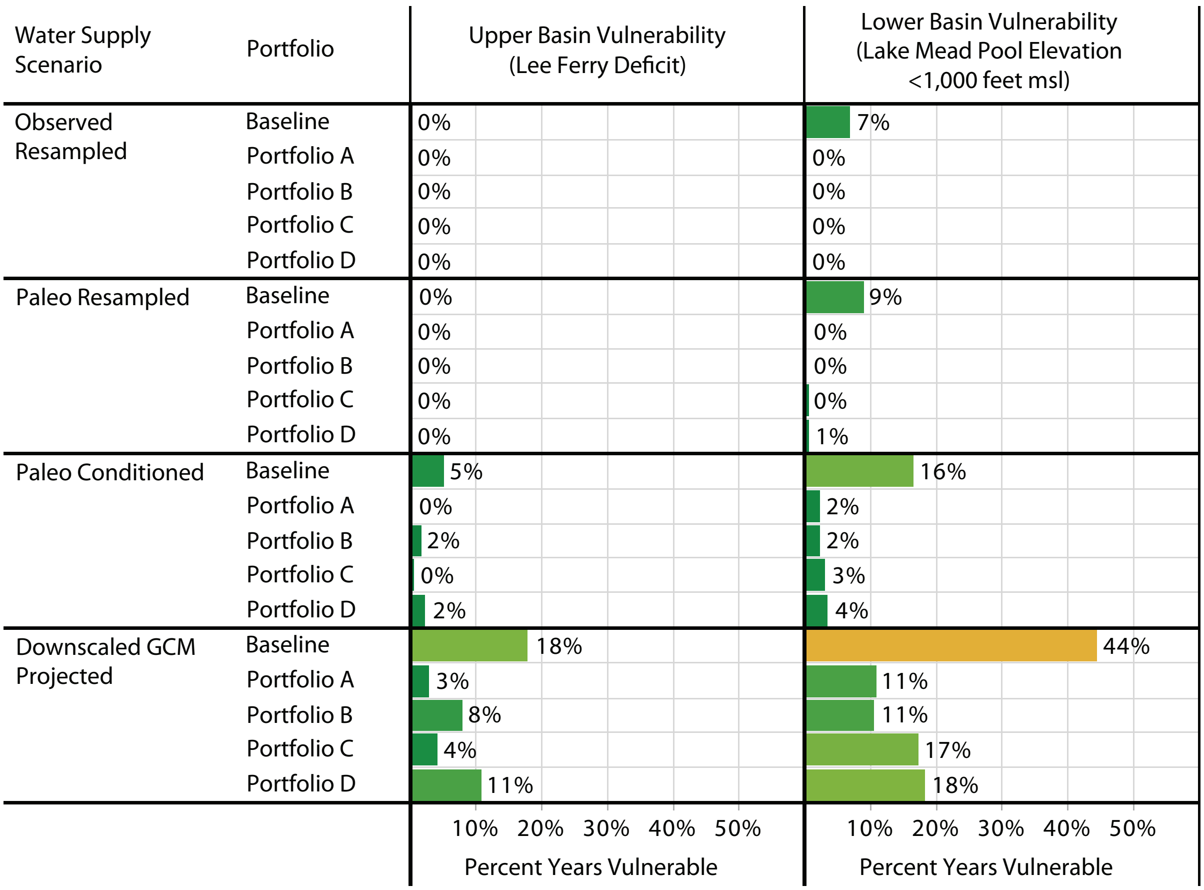
Although the portfolio analysis successfully demonstrated that system reliability can be improved, it is not without significant cost and performance tradeoffs. Figure 3 illustrates the performance across portfolios by water supply scenario in terms of addressing the critical Upper Basin and Lower Basin vulnerabilities.

Portfolio B favors options believed to have higher certainty of available water supply once implemented. As shown on the right side figure 3, this portfolio performs as well or better than all the other portfolios for addressing the Lower Basin vulnerability. The portfolio is less effective than *Portfolios A and C* for the Upper Basin vulnerability (figure 3, left side), particularly in the Downscaled GCM Projected supply scenario (bottom row).

Portfolio C, while focused on options that favor lower energy needs and less environmental impacts, is more dependent on shifting social values towards additional water conservation and reuse. Choosing to implement options characterized as having low

FIGURE 3

Percent of Years Vulnerable for Upper Basin (left) and Lower Basin (right) Vulnerabilities in 2041–2060 with Portfolios, by Water Supply Scenario

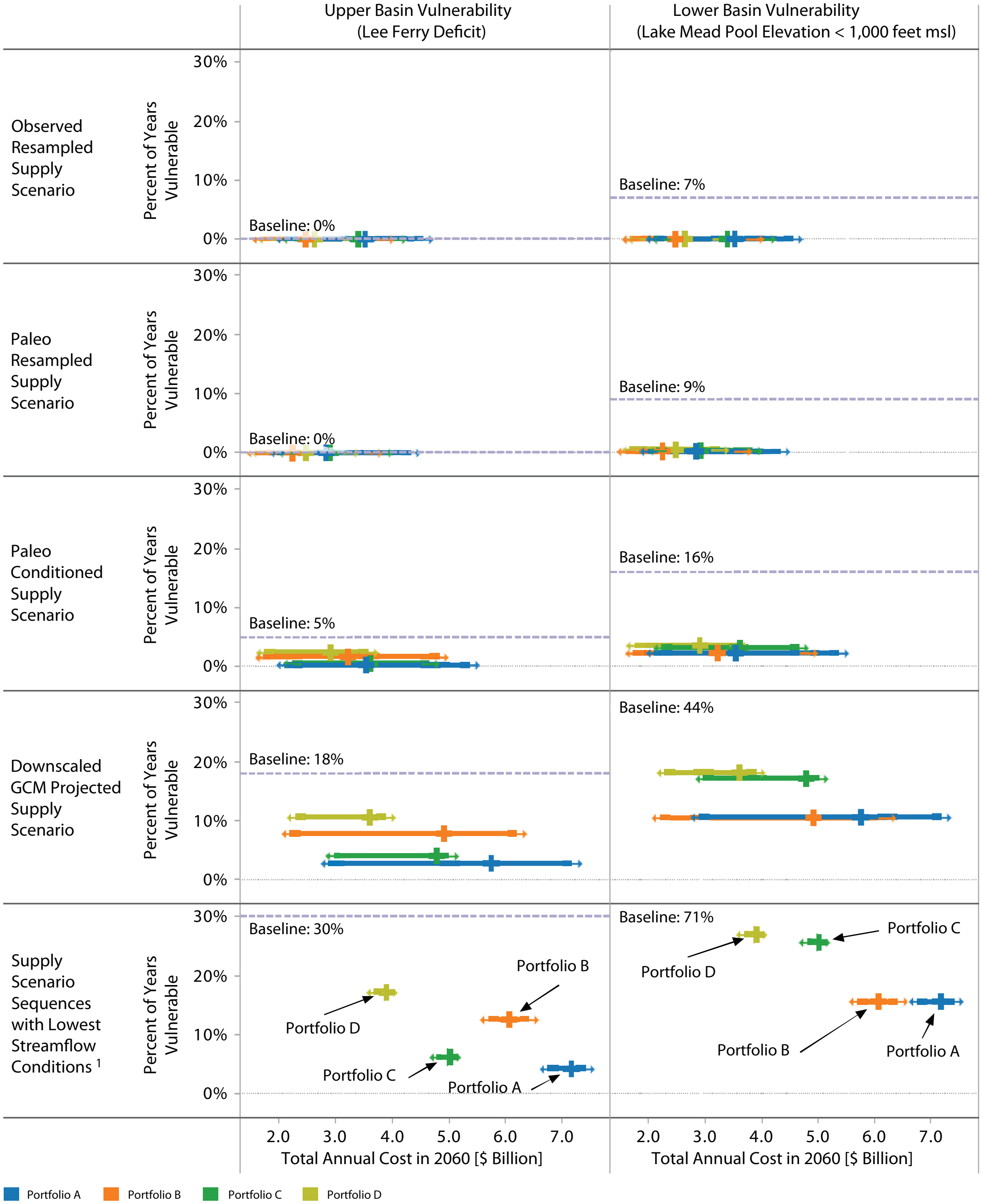


energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. However, this portfolio performs well for addressing the Upper Basin vulnerability (figure 3, left side) and is particularly effective under the Downscaled GCM Projected supply scenario (figure 3, bottom row). The effectiveness of this portfolio for addressing Upper Basin reliability vulnerabilities is largely attributable to the inclusion of an Upper Basin water bank that specifically targets this vulnerability. *Portfolio C* is less effective, however, at addressing the Lower Basin reliability vulnerabilities (figure 3, right side).

Tradeoffs also exist with respect to portfolio costs, and these differ depending on the specific future conditions. As shown in figure 4, the annual cost, in 2012 dollars, for implementing the portfolios ranges from approximately $2.5 billion to $3.5 billion in the year 2060 when considering the median of the Observed Resampled supply sequences, and from $3.6 billion to $5.8 billion when considering the median of the Downscaled GCM Projected supply sequences. The variability of the cost (reflected by the

FIGURE 4

Portfolio Cost and Percent of Years Vulnerable for Upper Basin (left) and Lower Basin (right) Vulnerability for 2041–2060 across Water Supply Scenarios and Lowest Streamflow Conditions



[1] Lowest Streamflow Conditions are defined as those in which the average of the 2012–2060 natural flow at Lees Ferry is less than 14 mafy and the lowest 8-year natural flow at Lees Ferry from 2012–2060 averages less than 11 mafy.

inter-quartile range or the length of the bars) reflects the varying size of the portfolios in different future conditions. Because of the appraisal-level option cost estimating used in the Study, the cost values contain additional uncertainty not directly reflected in these estimates. Across three supply scenarios (Observed Resampled, Paleo Resampled, and Paleo Conditioned), *Portfolios B* and *D* are generally shown to be less costly than *Portfolios A* and *C*. For the Downscaled GCM Projected water supply scenario tradeoffs between portfolios begin to become apparent. Specifically, *Portfolio C* leads to fewer vulnerable years with respect to Upper Basin vulnerability than *Portfolios A* and *B*, with an upper range of costs that is also lower than those for *Portfolios A* and *B*. Conversely, *Portfolio A* generally leads to the fewest vulnerable years with respect to Lower Basin reliability than other portfolios.

The differences among the portfolios become more apparent in terms of costs and ability to reduce vulnerability as one focuses on the future conditions that are particularly stressing to the Basin. For water supply conditions that are less favorable, such as in the "Lowest Streamflow" subset of sequences (figure 4, bottom row), two distinct tradeoffs between reduction in vulnerability and cost across the portfolios are apparent. For the Upper Basin vulnerability, *Portfolio C* both performs better than *Portfolios B* and *D* in terms of reducing this vulnerability and has a lower range of costs than *Portfolios A* and *B*. For the Lower Basin vulnerability, however, *Portfolio B* reduces vulnerability more than *Portfolios C* and *D* and also results in lower costs than *Portfolio A*.

Although the portfolios explored in the Study address water supply and demand imbalances differently, there are commonalities across the options implemented for each portfolio. All of the portfolios incorporate significant agricultural water conservation, M&I water conservation (1 maf each of both additional M&I and agricultural conservation was implemented in all portfolios), energy water use efficiency, and some levels of weather modification. However, some options were implemented more frequently in response to challenging water supply conditions. For example, ocean and brackish water desalination, wastewater reuse, and importation options were implemented for the most challenging water supply conditions in portfolios in which they were included. Future planning will require careful consideration of the timing, location, and magnitude of anticipated future Basin resource needs. The purpose of exploring these portfolios is not to identify a "best" portfolio or strategy, but to acknowledge that there are various ways to address the water supply and demand imbalance and to recognize that each approach has implications to be considered in future planning processes and decision-making.

5.0 Study Limitations

Although the technical approach of the Study was based on the best science and information available, as with all studies, there were limitations. The detail at which results are reported or the depth to which analyses were performed in the Study was limited by the availability of data, assessment methods, and the capability of existing models. These limitations provide opportunities for additional research and development and the improvement of available data, which will be pursued in efforts independent of the Study. Notable Study limitations include the following:

- **Ability to Assess Impacts to Basin Resources** – The ability to assess impacts to Basin resources, particularly in the Upper Basin, was limited by the spatial and temporal detail of the Colorado River Simulation System (CRSS), the primary model used in the Study. In particular, the Study's assessment of water deliveries at local level, and ecological and recreational impacts were affected by these limitations. Future efforts will evaluate ways to improve the assessment of these resources in future studies which will include enhancements to CRSS, as appropriate.

- **Treatment of Lower Basin Tributaries** – CRSS uses historical inflows (not natural flows) based on USGS streamflow records for four tributaries below Lees Ferry (the Paria, Little Colorado, Virgin, and Bill Williams rivers). In addition, the Gila River is not included in CRSS. The current treatment of these tributaries limited the ability of the Study to fully assess the natural supply of the Basin, and the data and methodological inconsistencies present in the Reclamation's Consumptive Uses & Losses Reports limited the ability of the Study to gain a more complete understanding of historical consumptive use in the Basin. The Basin States will also work with Reclamation in

Lake Powell, formed by Glen Canyon Dam




fulfilling the commitments regarding the Lower Basin tributaries specifically described in *Technical Report C – Water Demand Assessment, Appendix C11*.

- **Treatment of Agricultural Land Use in Water Demand Scenarios** – The development of the water demand storylines included participation from a broad range of stakeholders. The storylines were developed to represent a range of plausible futures regarding future demand. However, the assumptions in some storylines with regard to key driving forces resulted in the same directional changes in demand across the storylines. For example, the assumptions of continued conversion of agricultural land use to urban land use and lower-economic value crops being phased out in some areas led to overall agricultural land use (i.e., the number of irrigated acres) decreasing over time over all scenarios. Although some scenarios do show increasing agricultural land use at a state and local level, given recent projections of increased agricultural productivity necessary to meet future food needs, plausible futures should include increases in land use.

- **Option Characterization Process** – The option characterization process strived for objectivity and consistency. The limitations identified during the characterization process included geographic limitations due to the extensive size of the basin and regional variety, the appraisal-level of the analysis, potential subjectivity during the characterization process, and significant uncertainty due to limited data. Specifically for those options associated with agricultural and M&I conservation and reuse, a detailed assessment by individual location for those options was not performed. Instead, these options were characterized at a Basin-wide level. The resulting assumptions were adopted for purposes of the Study and do not necessarily reflect achievable, or even desirable, local conservation goals for individual municipalities or agricultural locations. Further, not all stakeholders in the Study were in agreement with all characterization results, but recognized that future efforts beyond the Study should result in more in-depth assessments of the options and reduced uncertainty.


Bill Williams River, Arizona

- **Consideration of Options** – Due to the legal, regulatory, and sometime technical complexity of the options submitted, not all categories of options submitted underwent a quantitative assessment. As such, portfolios were largely limited to groups of options that lend themselves to modeling implementation within the Study’s timeframe, i.e. those that increase supply or reduce demand, with the exception of the Upper Basin water bank concept. The options modeled in CRSS do not necessarily reflect the entire range of innovative options and strategies that should continue to be explored in future efforts.

Reclamation. 2017.Colorado River Basin Water Supply and Demand Study. Executive Summary.

6.0 Future Considerations and Next Steps

Colorado River water managers and stakeholders have long understood that growing demands on the Colorado River system, coupled with the potential for reduced supplies due to climate change may put water users and resources relying on the river at risk of prolonged water shortages in the future. The magnitude and timing of these risks differ spatially across the Basin. In particular, areas where demand is at or exceeds available supply are at greater risk than others. The Study builds on earlier work and is the next significant step in developing a comprehensive knowledge base and suite of tools and options that will be used to address the risks posed by imbalances between Colorado River water supply and resource needs in the Basin.

The Study confirms that the Colorado River Basin faces a range of potential future imbalances between supply and demand. Addressing such imbalances will require diligent planning and cannot be resolved through any single approach or option. Instead, an approach that applies a wide variety of ideas at local, state, regional, and Basin-wide levels is needed. The Study's portfolio exploration demonstrated that implementation of a broad range of options can reduce Basin resource vulnerability and improve the system's resiliency to dry hydrologic conditions while meeting increasing demands in the Basin and adjacent areas receiving Colorado River water.

The Study confirms that the Colorado River Basin faces a range of potential future imbalances between supply and demand. Addressing such imbalances will require diligent planning and cannot be resolved through any single approach or option.

The Study indicates that targeted investments in water conservation, reuse, and augmentation projects can improve the reliability and sustainability of the Colorado River system to meet current and future water needs. Ultimately, the Study is a call to action. To implement the water conservation, reuse, and augmentation projects identified in the Study, significant additional efforts are required immediately. These additional efforts, or next




Deadhorse Point overlook, Colorado River in Utah

steps, include a commitment to further analysis and planning in many areas related to the Study.

In summary, there are several future actions that must take place to move closer towards implementing solutions to resolve imbalances in the Basin. First, significant uncertainties related to water conservation, reuse, water banking, and weather modification concepts must be resolved in order to adequately implement these approaches. Second, costs, permitting issues, and energy needs relating to large-capacity augmentation projects need to be identified and investigated through feasibility-level studies. Third, opportunities to advance and improve the resolution of future climate projections should be pursued and enhancements to the operational and planning tools used in the Colorado River system to better understand the vulnerabilities of the water-dependent uses, including environmental flows, should be explored. Fourth, as projects, policies, and programs are developed, consideration should be given to those that provide a wide-range of benefits to water users and healthy rivers for all users.

In recognition of their ongoing joint commitment to future action, Reclamation will convene the Basin States along with tribes, other Colorado River water entitlement holders, conservation organizations, and other interested stakeholders in early 2013 to conduct a workshop to review the recommended next steps and initiate actions to implement next steps to resolve the current and potentially significant future imbalances in the Colorado River system. In early 2013 Reclamation will also consult and work with tribes regarding tribal water issues reflected in this report.

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 the 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, any federally recognized tribe, 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, any federally recognized tribe, Federal government or Upper Colorado River Commission as it relates to the law of the river. Furthermore, nothing in the Study is intended to, nor shall the Study be construed so as to, interpret, diminish or modify the rights of any Basin State, any federally recognized tribe, 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, or Minute No. 319 of November 20, 2012, 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) as amended, the Hoover Power Plant Act of 1984 (98 Stat. 1333), the Colorado River Floodway Protection Act (100 Stat. 1129; 43 U.S.C. 1600), the Grand Canyon Protection Act of 1992 (Title XVIII of Public Law 102-575, 106 Stat. 4669), or the Hoover Power Allocation Act of 2011 (Public Law 112-72). In addition, nothing in the Study is intended to, nor shall the Study be construed so as to, interpret, diminish or modify the rights of any federally recognized tribe, pursuant to Federal Court Decrees, State Court Decrees, treaties, agreements, executive orders and federal trust responsibility. Reclamation and the Basin States continue to recognize the entitlement and right of each State and any federally recognized tribe under existing law, to use and develop the water of the Colorado River system.