UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

	)	
Navajo Energy Storage Station, LLC	)	Project No. 15001-000
	)	
	)	**MOTION TO INTERVENE BY**
Preliminary Permit Application for	)	**WILDEARTH GUARDIANS and**
Navajo Energy Storage Station Pumped	)	**SAVE THE COLORADO**
Storage Project	)	
	)	
______________________________________	)	

INTRODUCTION

On July 1, 2019, Navajo Energy Storage Station, LLC ("NES") filed an application for a preliminary permit for the Navajo Energy Storage Station Pumped Storage Project ("the Project") (Project Number 15001-000). On January 14, 2020, the Federal Energy Regulatory Commission ("the Commission") filed the Notice of Successive Preliminary Permit Application Accepted for Filing and Soliciting Comments, Motions to Intervene, and Competing Applications. On January 15, 2020, the Commission issued an Errata correcting the Notice title. Pursuant to the Notice and Rule 214 of the Commission's Rules of Practice and Procedure, 18 C.F.R. § 385.214, Save the Colorado and WildEarth Guardians hereby timely move to intervene in the preliminary permit proceeding and oppose the requested license.

INTERESTS OF INTERVENORS

I. Save the Colorado's Interest

Save the Colorado is a grassroots, non-profit 501(c)(3) environmental organization dedicated to the protection and restoration of the Colorado River and its tributaries. Save the Colorado has approximately 20,000 members, supporters, and followers throughout the Colorado River Basin, including within Arizona. Save the Colorado's mission is to promote the conservation of the Colorado River and its tributaries through science, public education, advocacy, and litigation, by opposing new dams and diversions. Save the Colorado has actively opposed every proposed new dam, diversion, and pipeline in the Colorado River basin—including in Colorado, Wyoming, and Utah—through litigation and pre-permitting processes. Recently, Save the Colorado opposed the Bureau of Reclamation's management plan for Glen Canyon Dam, which regulates the Colorado River's flows through the Grand Canyon. *See, e.g.*, Compl., ECF No. 1, *Save the Colo. v. U.S. Dep't of the Interior*, No. 3:19-cv-08285-MTL (D. Ariz. Oct. 1, 2019).

II. WildEarth Guardians' Interest

WildEarth Guardians is a regional non-profit dedicated to protecting and restoring the wildlife, wild places, wild rivers, and health of the American West. Guardians has over 275,000 members and activists nationwide and maintains offices in Santa Fe, Denver, Missoula, Portland, Seattle and Tucson. For over 30 years, Guardians has worked to safeguard and restore dynamic flows in western rivers, advocated for western water policy reform, ensured protection of imperiled fish and wildlife, and fought to undam and restore healthy and sustainable aquatic and riparian ecosystems for future generations. Recently, Guardians and its allies filed federal court litigation challenging the permitting of two water development projects in the Upper Colorado River Basin including the Windy Gap Firming Project and Moffat Collection System Project. In addition, Guardians recently intervened in the preliminary permit applications for the Navajo Nation Salt Trail Canyon Pumped Storage Project (No. 14992-000) and the Navajo Nation Little Colorado River Pumped Storage Project (No. 14994-000). Guardians has devoted significant resources over the past 30 years to advocate for living rivers, combat the extinction crisis, and promote climate resilience.

III. Save the Colorado's and WildEarth Guardians' Intervention is in the Public Interest

Save the Colorado's and WildEarth Guardians' intervention is in the public interest. *See* 18 C.F.R. § 385.214(b)(2)(iii). Each organization represents a cross-section of members that have unique and direct interests in the Little Colorado River, the Glen Canyon National Recreation Area, and Lake Powell that the Project will harm if it proceeds. The organizations have direct and tangible interests in protecting the Little Colorado River and Lake Powell, and in preserving the wildlife and recreation activities that rely on healthy rivers and lakes. Their members use and enjoy the areas affected by the proposed pumped storage project for aesthetic enjoyment, spiritual renewal, and recreation, including rafting, fishing, camping, hiking, photography, wildlife viewing, and enjoyment of the outdoors. Many members rely on these waterways and the nearby lands for their recreational, scientific, educational, cultural, conservation, and economic interests.

The Project would harm these interests. Save the Colorado and WildEarth Guardians are concerned that climate change affecting the Colorado River Basin renders unviable Lake Powell and any hydroelectric project dependent on Lake Powell. Save the Colorado's and WildEarth Guardians' experiences with climate change and its effects on the Colorado River Basin position them to offer important scientific information that will help to inform the Commission in making the decision whether to permit the Project. Specifically, Save the Colorado and WildEarth Guardians are concerned that the Proposal does not consider how climate change will render an already-depleted Lake Powell a non-viable water source for a hydroelectric project. No other party can adequately represent these same interests.

In addition, many of the members of Save the Colorado and WildEarth Guardians have special knowledge of the Commission's preliminary permit proceedings, as they intervened in the preliminary permit applications for the Navajo Nation Salt Trail Canyon Pumped Storage Project (No. 14992-000) and the Navajo Nation Little Colorado River Pumped Storage Project (No. 14994-000). Save the Colorado also intervened in the Wyco Power and Water preliminary permit proceeding for the Flaming Gorge Pipeline and successfully opposed a preliminary permit for that project. *See Wyco Power & Water, Inc.*, 138 FERC ¶ 62,150 (2012) (denying preliminary permit application). These groups and their members have developed knowledge and relevant experience regarding preliminary permits and hydropower projects that will benefit the public interest in this proceeding.

Save the Colorado and WildEarth Guardians will actively participate in this preliminary permit process and in any subsequent licensing proceeding to ensure the protection of the Little Colorado River, Lake Powell and the Glen Canyon National Recreation Area. This participation will lead to more informed decision making, develop a more complete record, and be in the public interest. Accordingly, Save the Colorado and WildEarth Guardians request intervention on behalf of themselves and their members.

FACTUAL BACKGROUND

The Colorado River is one of our nation's largest rivers and supplies water to residents of seven states in the American Southwest. The river begins in the Rocky Mountains in Colorado and flows 1,450 miles until reaching Mexico. Its basin covers an immense 246,000 square miles. The Colorado River is an important waterway that supports a wide range of ecologically significant species and communities, has a long cultural history, and is a critical source of water for millions of people and numerous water-dependent industries.

The Colorado River was, until the construction of the Dam, free-flowing through Glen Canyon, renowned for its massive sandstone cliffs and vistas. In 1963, the construction of the Glen Canyon Dam was completed. The Dam's reservoir, Lake Powell, is located on the northward side of the facility.

Climate change and its respective environmental impacts, such as water scarcity due to climate change-related droughts, have contributed to drastic declines in the water levels of Lake Powell in recent years. Lake Powell is now surrounded by a "bathtub ring" indicating the water body's former high-water mark. The Lake currently sits more than 80 feet below this mark. Rising global temperatures transform what would have been "modest droughts" historically "into severe ones." Recent research indicates that the precipitation levels needed to offset rising temperatures in the Colorado River Basin are highly unlikely to occur.[1]

LEGAL BACKGROUND

The purpose of the Federal Power Act (FPA) is to promote balanced and responsible hydropower development. The FPA authorizes the Commission to license private hydropower projects, but requires the Commission to weigh the power generation and developmental goals of a project against impacts to fish, wildlife, recreation, and other resources before issuing a license. 16 U.S.C. § 797(e); *Udall v. Fed. Power Comm'n*, 387 U.S. 428, 450 (1967); *Am. Rivers v. Fed. Energy Regulatory Comm'n*, 201 F.3d 1186, 1191 n.6 (9th Cir. 2000); *Symbiotics, LLC*, 99 FERC ¶ 61,100, at 61,417 (2002).

The FPA also authorizes the Commission to issue preliminary permits for potential hydropower projects. 16 U.S.C. § 798; 18 C.F.R. § 4.80. According to the Commission, the "purpose of a preliminary permit is to encourage hydroelectric development" by providing a permit holder a first-in-time right to file a license application to construct and operate a hydropower project while the permit holder determines the feasibility of the project and prepares the license application. *Mt. Hope Waterpower Project LLP*, 116 FERC ¶ 61,232, at ¶ 4 (2006).

The Commission has "broad discretion" to determine whether to issue a preliminary permit. *Symbiotics, LLC*, 100 FERC ¶ 61,010, at 61,018 (2002); *see also Preliminary Permits for Wave, Current, and Instream New Technology Hydropower Projects* (Docket No. RM07-08-000), at 3 n.9 (Feb. 15, 2007) ("[N]othing in the FPA requires the Commission to issue a preliminary permit; whether to do so is a matter solely within the Commission's discretion."). Although the Commission's general policy is to defer analysis of a project's impacts until the

[1] Bradley Udall & Jonathan Overpeck, *The twenty-first century Colorado River hot drought and implications for the future*, 53 WATER RESOURCES RES. 2402, 2408 (2017). (Attachment 1).

later licensing proceedings, the Commission has discretion to deny a preliminary permit application at any time, so long as "it articulates a rational basis for not issuing the permit." *Wyco Power & Water, Inc.*, 139 FERC ¶ 61,124, at 61,852 (2012); *see also Mt. Hope Waterpower*, 116 FERC ¶ 61,232, at ¶ 4 ("We may, however, make exceptions to established policies if we articulate a rational basis for doing so, and we have recently done so with regard to issuance of preliminary permits in other proceedings."). The Commission has exercised this discretion on a number of occasions.

The Commission has routinely dismissed preliminary permit applications when there is a legal bar that would prevent the Commission from granting a license for the project. *See, e.g.*, *Energie Grp.*, 511 F.3d at 164; *Seneca Nation of Indians*, 134 FERC ¶ 62,148, at 64,246 (2011); *Appalachian Rivers Res. Enhancement, LLC*, 113 FERC ¶ 62,100, at 64,288. Similarly, the Commission will deny a permit where the "information already available indicates no license will result." *Energie Grp.*, 511 F.3d at 164. For example, the Commission properly denied a preliminary permit when it found a prior environmental analysis for a project was "analogous" to a legal barrier, as the analysis indicated the project was not appropriate for the site and thus no license would likely result. *Symbiotics, L.L.C. v. Fed. Energy Regulatory Comm'n*, 110 F. App'x 76, 81 (10th Cir. 2004).

The Commission will also deny a preliminary permit if the applicant is unlikely to receive the necessary authorizations to develop the project, as "there would be no purpose in issuing a preliminary permit" in those circumstances. *Freedomworks, LLC*, 167 FERC ¶ 62,026 at ¶ 11 (2019); *see also Advanced Hydropower, Inc.*, 160 FERC ¶ 62213, at ¶ 6 (2017) (denying permit where a federal agency had already stated that the proposed project was incompatible with federal purposes); *Symphony Hydro LLC*, 150 FERC ¶ 62,092, at 64,165 (2015) (same);

Owyhee Hydro, LLC, 154 FERC ¶ 61,210, at ¶¶ 22–25 (2016) (affirming denial of permit where the relevant agency stated the applicant's proposed use was unacceptable and would not be permitted).

Finally, the Commission has denied preliminary permits where it found that the proposed project—or further study of the proposed project—would be contrary to the public interest. *See, e.g.*, *Stillaquamish River Hydro*, 40 FERC ¶ 62,207, at 63,356 (1987) (proposed project not in the public interest because it would interfere with military communications and threaten national security); *Mt. Hope Waterpower*, 116 FERC ¶ 61,232, at ¶¶ 5, 12, 13, 15–17 (public interest served by denying preliminary permit to allow competition).

ARGUMENT AND STATEMENT OF POSITION

On July 1, 2019, NES filed the application for the preliminary permit, proposing to analyze the feasibility of building the Project at Lake Powell in San Juan County, Arizona. The permit would give NES priority in filing a licensing application, but does not give the permit holder any land rights. Specifically, the permit holder may not engage in land-distribution or otherwise enter land or water owned by others without the owner's permission.

The proposed Project would use the Lake Powell Reservoir, created by the Glen Canyon Dam, and would consist of: (1) a 15,150-foot-long, 131-foot-high rockfill concrete dam with a storage capacity of 18,600 acre feet; (2) an approximately 6,550-foot-long water conveyance structure between the reservoir and Lake Powell, including one 35-foot diameter tunnel, eight 11-foot diameter penstocks, eight 15-foot diameter draft tubes, and two 31-foot diameter tailrace tunnels; (3) a powerhouse containing eight turbine generating units with a combined capacity of 2,210 megawatts; (4) an 18-mile long, 500 kilovolt transmission line connecting to the existing

230 kilovolt power lines; and (5) appurtenant facilities. The Project's estimated annual power generation is 3,365 gigawatt hours.

The Project Application fails to provide meaningful information and Project feasibility in light of the impacts that climate change and its concomitant drought conditions will have on flow, water levels, and water availability of the Colorado and Little Colorado Rivers, and Lake Powell. Therefore, the Project Application is incomplete and inaccurate and should be denied.

First, the Application fails to acknowledge that the Colorado River's average annual flow has decreased within the past two decades by approximately 20% compared to 20th century flows, half of which is due to climate change since 2000. This decrease equals 1.5 billion tons of unavailable water in the River.[2] Thus, the Project may not be feasible in light of already-reduced river flows.

Second, the Application fails to acknowledge how close Lake Powell is to extinction, potentially rendering infeasible any reliance on being able to withdraw water from Lake Powell. The General Manager of the Colorado River District recently proposed an increase of electric rates across the Southwest U.S.[3] This increase would enable the District to lease 500,000-acre feet of water from Colorado farmers to ensure that dwindling Lake Powell has sufficient water to create hydropower and to meet its discharge requirements. The District's concerns about Lake Powell stem from reduced water levels caused by climate change. This ill-conceived plan would only enable Glen Canyon Dam to release the required discharge for water for 22 days. Any

---

[2] P.C.D. Milly & K.A. Dunne, *Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation*, SCIENCE MAGAZINE (2020). (Attachment 2).

[3] Heather Sackett, *Who should pay for water conservation in the West? Water managers wade into discussion*, Aspen Journalism (2019), https://www.aspenjournalism.org/2019/12/30/who-should-pay-for-water-conservation-in-the-west-water-managers-wade-into-discussion/. (Attachment 3).

additional hydropower project on Lake Powell, such as the Project at issue in this proceeding, would thus be inefficient and against the public interest given Lake Powell's already low levels.

Third, the Application fails to acknowledge resent research indicating that the water temperature in the Colorado River is rising because of climate change. This warming temperature trend will reduce the quality of water in and flowing from Lake Powell because warmer temperatures may increase the likelihood of algal blooms.[4] The Application does not discuss the impact of water temperature on flows and potential impacts to Project feasibility as a result.

Fourth, the Application fails to acknowledge that climate change models predict that drought intensity and duration will increase along the Colorado River Basin, making the effects of climate change greater than originally assumed.[5] Droughts intensified by climate change could completely drain existing water storage[6] and dramatically reduce Colorado River flow into Lake Powell because of evaporation and evapotranspiration.[7] Furthermore, water temperature in the Colorado River is rising because of climate change. [8] The amount of rain water required to offset rising temperatures is unlikely to occur.[9] Thus, any hydroelectric project along the Colorado River may become infeasible during the life of the project.

Finally, the Application fails to acknowledge that U.S. Bureau of Reclamation projections cite the possibility that Lake Powell may become so low because of climate change that Glen Canyon Dam will be unable to produce hydropower. Furthermore, the Bureau found

---

[4] Udall & Overpeck, *supra* at 2404. *See also* Mu Xiao et al, *On the Causes of Declining Colorado River Streamflows*, 54 WATER RESOURCES RES. 6739 (2018). (Attachment 4)
[5] Udall & Overpeck, *supra* at 2404.
[6] George Rhee & Jimmy Salazar, *How Long Does a 15-Year Drought Last? On the Correlation of Rare Events*, 32 J. OF CLIMATE 1345 (2018). (Attachment 5)
[7] Bureau of Reclamation, Colorado River Basin Water Supply and Demand Study (2012).
[8] Udall & Overpeck, *supra* at 2408.
[9] Bradley & Overpeck, *supra* at 2413.

that the imbalances between water supply and demand along the Colorado River Basin will be 3.2 million-acre feet by 2060.[10] These possibilities raise questions about the feasibility of any hydroelectric project at Lake Powell given the increasing demands on Colorado River water and dwindling supply.

The Project is ill-conceived in light of climate change's effects on the Colorado River and Lake Powell. Lake Powell is not a reliable water source under current environmental conditions, barely surviving the detrimental effects of climate change and incapable of recovering. Increasing water temperature, the risk of increasingly intense and long droughts, and decreasing water levels with increasing demand render Lake Powell an infeasible location for any additional hydropower projects. For these reasons, Save the Colorado and WildEarth Guardians urge the Commission to deny the requested preliminary permit for the Navajo Energy Project.

SERVICE

Save the Colorado and WildEarth Guardians request that the Commission include the following representatives to the official service list for this proceeding, along with WildEarth Guardian' undersigned counsel:

Gary Wockner, PhD
Save the Colorado
P.O. Box 1066
Fort Collins, CO 80522
(970) 218-8310
gary@savethecolorado.org

Jen Pelz, J.D.
WildEarth Guardians
2590 Walnut Street
Denver, CO 80205
303-884-2702

[10] Bureau of Reclamation, *Supra*, Colorado River Basin Water Supply and Demand Study. (Attachment 6).

jpelz@wildearthguardians.org

Samantha Ruscavage-Barz, J.D. (counsel for WildEarth Guardians)
WildEarth Guardians
301 N. Guadalupe St., Ste. 201
Santa Fe, NM 87501
(505) 401-4180
sruscavagebarz@wildearthguardians.org

CONCLUSION

WHEREFORE, Save the Colorado and WildEarth Guardians request the Commission grant its motion to intervene in this proceeding (P–15001–0000).

Dated: March 16, 2020.

Respectfully submitted,

Samantha Ruscavage-Barz

Samantha Ruscavage-Barz, Managing Attorney
WildEarth Guardians
301 N. Guadalupe St., Ste. 201
Santa Fe, NM 87501
(505-401-4180)
sruscavagebarz@wildearthguardians.org

Gary Wockner

Gary Wockner, PhD
Save the Colorado
P.O. Box 1066
Fort Collins, CO 80522
(970) 218-8310
gary@savethecolorado.org

CERTIFICATE OF SERVICE

I hereby certify that in accordance with 18 C.F.R. § 385.2010, on March 16, 2020, I served the foregoing document upon each person designated on the official service list compiled by the Secretary of the Federal Energy Regulatory Commission for this proceeding.

Samantha Ruscavage-Barz

Samantha Ruscavage-Barz

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

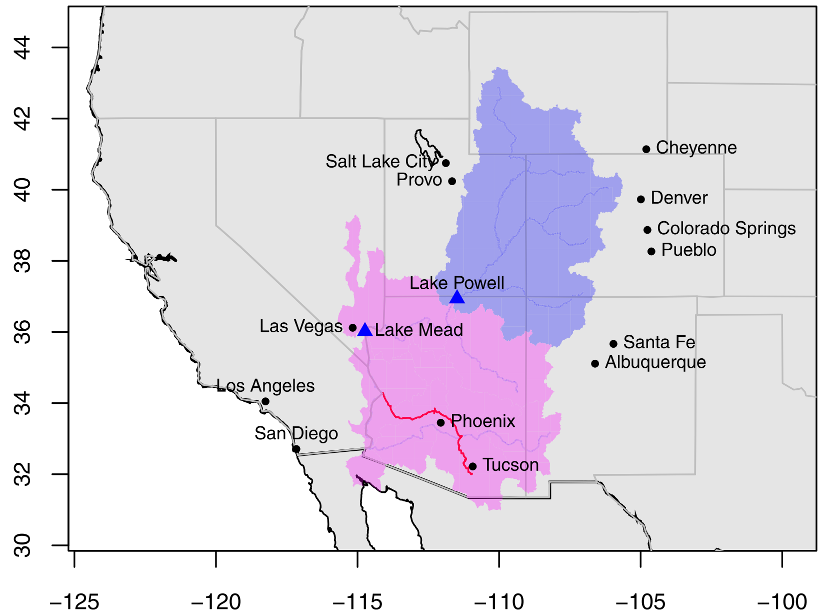


Figure 1. Map of the Colorado River Basin. Lower and Upper Basins, major U.S. cities receiving Colorado River water, major tributaries, and Lakes Mead and Powell are shown. The Central Arizona Project canal in red.

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

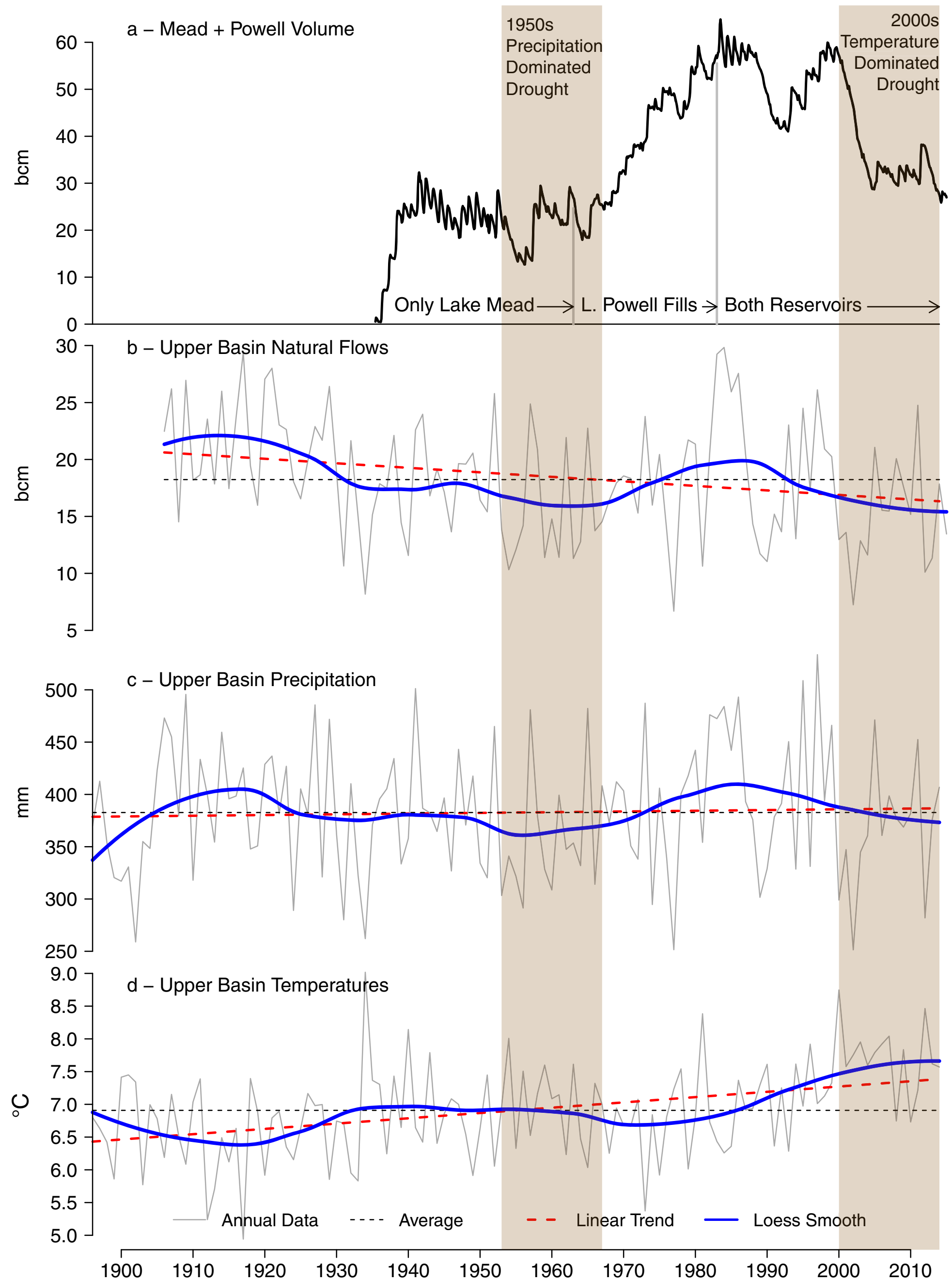


Figure 2. (a) Lakes Mead and Powell combined monthly contents. Upper Basin annual Colorado River (b) runoff at Lees Ferry from 1906 to 2014, (c) precipitation and (d) temperatures from 1896 to 2014. Mead first filled in 1935, Powell in 1963 (supporting information Text S1). Two 15-year drought periods,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

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

	1953–1967 mm			2000–2014 mm			1896–2014 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 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

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

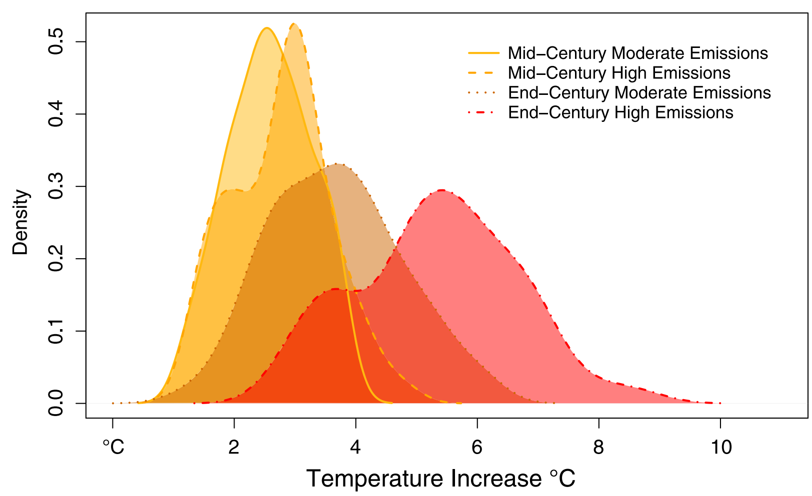


Figure 3. Probability density functions of Upper Colorado River Basin temperature projections for midcentury and end-century under moderate (SRES A1B and RCP4.5) and high (SRES A2 and RCP8.5) emissions.

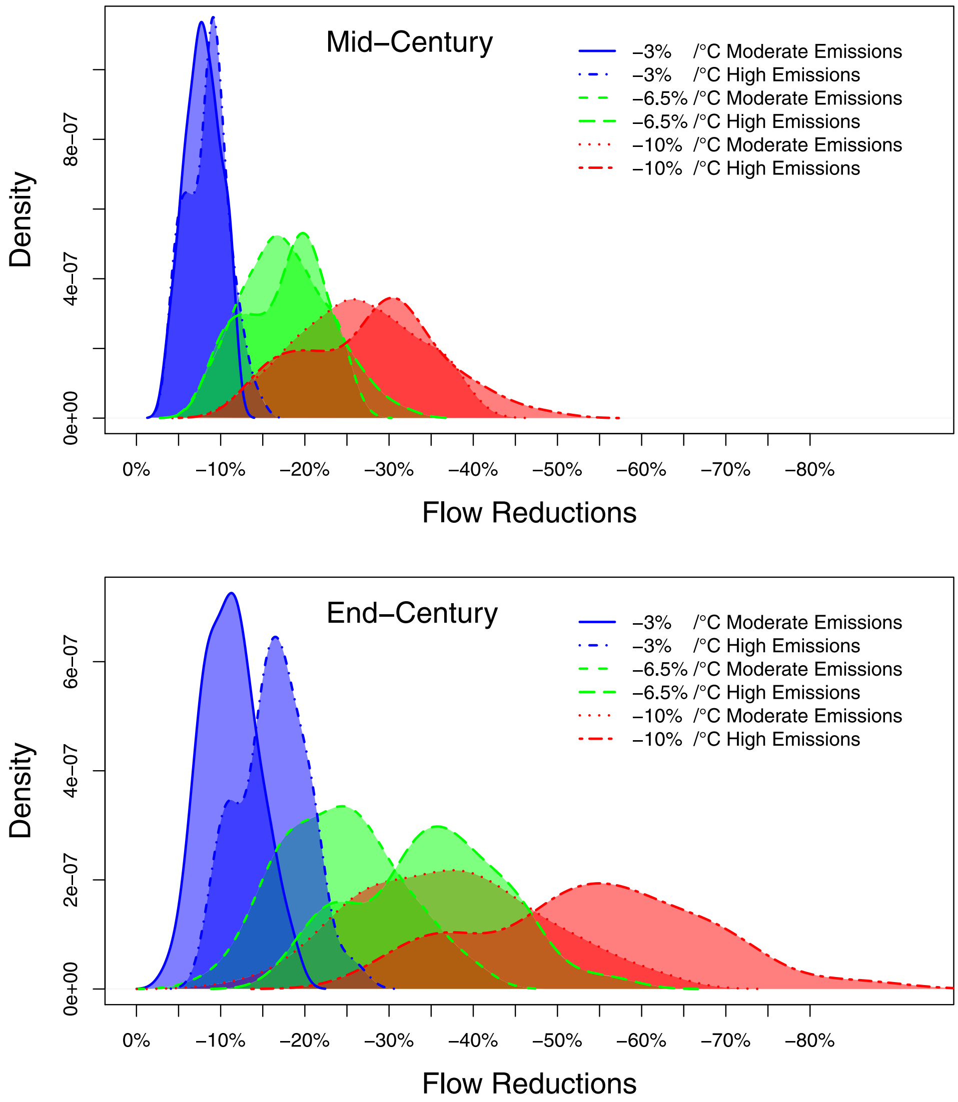


Figure 4. Probability density functions of Upper Colorado River Basin temperature-induced flow reductions for midcentury and end-century with the three temperature sensitivities (−3%, −6.5%, −10%) and the two levels of emissions (Moderate: SRES A1B and RCP4.5 and High: SRES A2 and RCP8.5).

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.*,

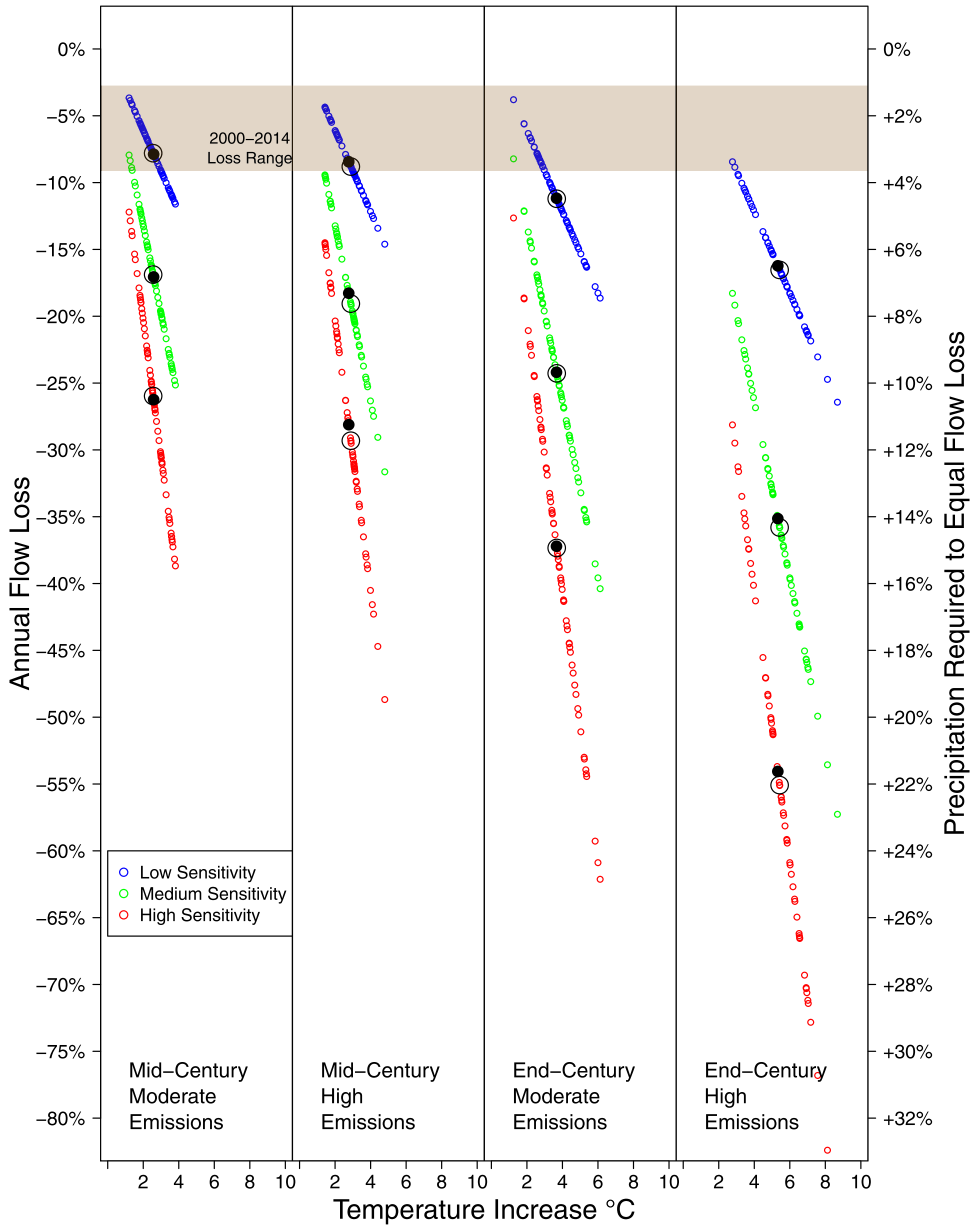


Figure 5. Temperature-induced flow losses by model run (one per dot) with temperature increases shown on horizontal axis. For each period (midcentury, end-century) and emissions type (moderate, high), flow losses for each model run are shown with the 3 (low = −3%/°C, medium = −6.5%/°C, high = −10%/°C) 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 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.

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 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.

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.

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.

WATER RESOURCES

Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation

P. C. D. Milly* and K. A. Dunne

The sensitivity of river discharge to climate-system warming is highly uncertain, and the processes that govern river discharge are poorly understood, which impedes climate-change adaptation. A prominent exemplar is the Colorado River, where meteorological drought and warming are shrinking a water resource that supports more than 1 trillion dollars of economic activity per year. A Monte Carlo simulation with a radiation-aware hydrologic model resolves the longstanding, wide disparity in sensitivity estimates and reveals the controlling physical processes. We estimate that annual mean discharge has been decreasing by 9.3% per degree Celsius of warming because of increased evapotranspiration, mainly driven by snow loss and a consequent decrease in reflection of solar radiation. Projected precipitation increases likely will not suffice to fully counter the robust, thermodynamically induced drying. Thus, an increasing risk of severe water shortages is expected.

The Upper Colorado River Basin (UCRB) supplies water to ~40 million people and supports ~16 million jobs (*1*). Atmospheric warming and recent precipitation deficits have heightened concern about the future (*2*–*6*), but the response of river discharge to warming remains highly uncertain. An implicit assumption in the literature on UCRB hydroclimatic change is that two climatic mean variables—precipitation and temperature—determine runoff (hence, river discharge) response, following constant sensitivities α [percent discharge change per percent precipitation change (dimensionless)] and β [percent discharge change per degree Celsius of warming (% °C^{-1})]. Empirical regression analyses imply large values of β (–13 to –15% °C^{-1}) (*4*, *6*–*8*), which is inconsistent with estimates in the range –2 to –9% °C^{-1} obtained from perturbation of temperature inputs (the delta method) to hydrologic model simulations (*2*, *9*, *10*) and from theory (*11*). For α, regression and delta estimates are in much better agreement (*10*). The discrepancy in β, which is seen for rivers around the globe (*11*), translates into great uncertainty in the magnitude of future effects on human livelihood, economic activity, and ecosystem health. The situation is exacerbated by limited process understanding in the presence of hydroclimatic nonstationarity (*12*). The empiricism that is inherent in the regression approach, and even that which is inherent in the estimation of energy-driven evaporative demand in the hydrologic models (*13*), leaves the use of such methods for extrapolation of past observations to the future, under anthropogenic climate change, open to question. Accordingly, we gave special attention to surface net radiation—the ultimate driver of evapotranspiration—and to its modulation by snow-affected surface albedo (*14*) rather than relying on temperature measurements as a surrogate for energy availability. We found a strong influence of snow-affected albedo on radiation balance in the UCRB (Fig. 1) (*15*), which necessitated its consideration in a process-based estimation of β.

Herein, we address the following questions, in turn, by use of a monthly water-balance model grounded in a suite of observations: Does the model reproduce the historical regression-based β? What is the model's delta-based β, and why does it differ from the regression-based value? Can the two values be reconciled? What physical processes control β? How sensitive is our β estimate to the assumptions in our analysis? How much did warming contribute to the historical hydrological drying in the UCRB? What future changes in UCRB discharge can be expected?

In addition to the snow-water equivalent (SWE), albedo, and radiation measurements used to develop the relations in Fig. 1, we used observations of precipitation and temperature

U.S. Geological Survey, Princeton, NJ, USA.
*Corresponding author. Email: cmilly@usgs.gov

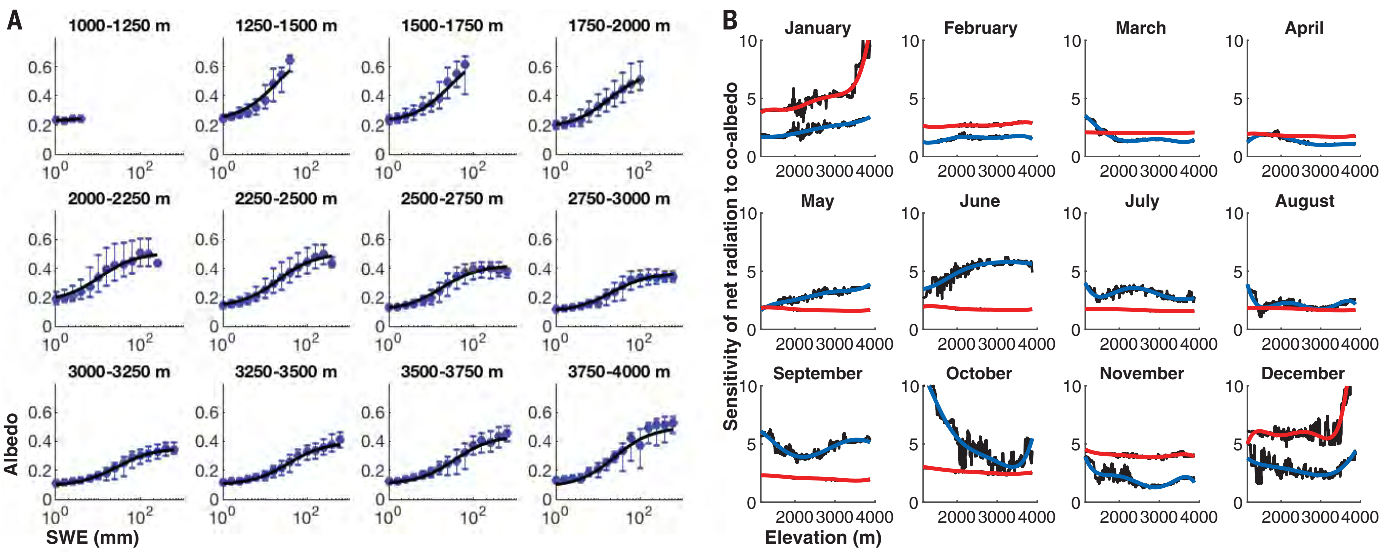


Fig. 1. Observed relations among monthly SWE, surface albedo, and surface net radiation in the UCRB. (**A**) Dependence of surface albedo on SWE (logarithmic scale) for each of 12 elevation ranges. 1st, 2nd, and 3rd quartiles of binned data are shown. Curves are least-squares fits to the unbinned data and are used in the model. (**B**) Inferred dimensionless sensitivity $\frac{C}{R_n}\frac{dR_n}{dC}$ of net radiation R_n to co-albedo (one minus albedo) C as a function of mean elevation of 960 subareas by month of the year. Blue curves are fitted to smoothed (30-point moving median; black) data from empirical regression estimates. Red curves are analogous fits for theoretical case where a change in absorbed solar radiation causes no radiative feedbacks. Fits to regressions are used in the model, except that fits to no-feedback data are used in a sensitivity experiment.

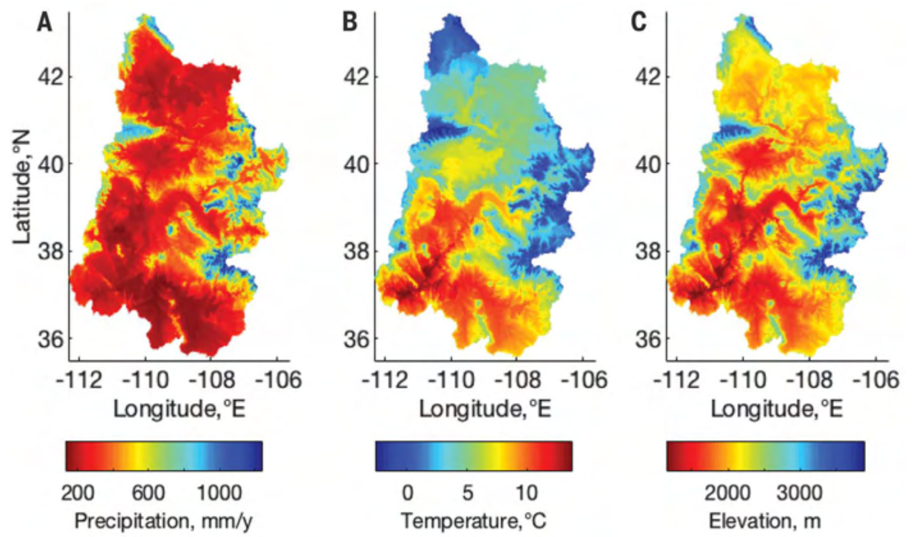


Fig. 2. Spatial distributions of annual climate variables and elevation over the UCRB, as resolved by the model discretization of space into 960 subareas. (**A**) Total precipitation. (**B**) Mean temperature. (**C**) Elevation.

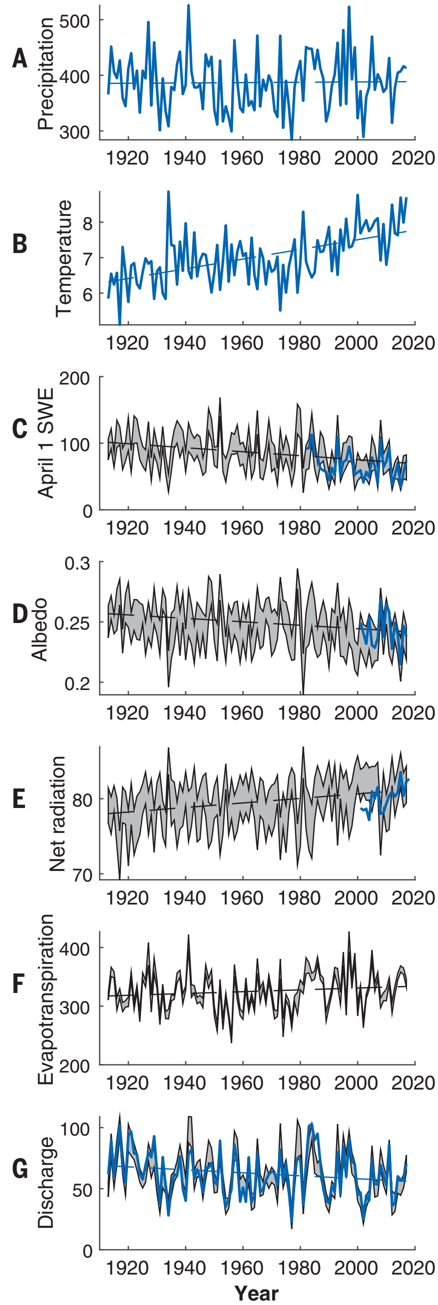


Fig. 3. Water-year time series of basin-mean, annual-mean values. (**A** to **G**) Precipitation (millimeters per year) (A), temperature (degrees Celsius) (B), April 1 SWE (millimeters) (C), surface albedo (D), surface net radiation (watts per square meter) (E), evapotranspiration (millimeters per year) (F), and discharge per unit area (millimeters per year) (G). Blue curves represent estimates from observations, and gray bands represent ensemble range of model outputs. Least-squares linear fits also are shown.

(Fig. 2 and Fig. 3, A and B) as well as discharge (Fig. 3G) to constrain a hydrologic simulation model (*15*), which we used to elucidate the processes that control sensitivity and to reconcile divergent, previously published sensitivity estimates. The model has a monthly time step and divides the 290,000-km^2 UCRB into 960 subareas to capture the strong heterogeneity induced by rugged (2700-m relief) topography (Fig. 2C). Rain-snow partitioning depends on temperature. Evaporative potential is set to the rate of non–water-stressed evapotranspiration under conditions of minimal advection (*16*). Fifteen model parameters were estimated by maximizing goodness of fit to observed discharge (*15*). We measured goodness of fit with respect to mean, linear trend, regression-based sensitivities α and β, and Nash-Sutcliffe coefficient of efficiency. [Including a correction that accounts for temporary subsurface storage of runoff before entering the river (*11*), which has previously been neglected, and using an October to September water year, we found observational regression-based α and β, ± one standard error of estimation, to be 1.98 ± 0.16 and −16.1 ± 2.9% °C^{-1}, respectively. Neglecting the storage correction yields β = −13.1 ± 2.4% °C^{-1}, consistent with earlier analyses.] The sensitivity of our results to the goodness-of-fit criteria is presented in the supplementary materials (*15*).

Of 500,000 trial parameter sets, 171 satisfied the goodness-of-fit criteria (*15*), and these formed a model ensemble for subsequent analyses. As the temperature rose, the ensemble-mean SWE and—hence, following the relations in Fig. 1—albedo decreased, which led to a basin-mean increase of net radiation by 3.0% per century over the study period (Fig. 3, C to E). With an associated increase in evapotranspiration (Fig. 3F), the ensemble mean–modeled annual discharge (Fig. 3G) fell by 20.1% per century, compared with 19.6% per century observed; the square of the correlation coefficient (r^2) between the observed and ensemble mean–modeled annual discharge is 0.82. Within the ensemble, the models' regression-based, storage-corrected sensitivities α and β ranged from α = 1.89 ± 0.16 to 2.08 ± 0.18 (mean, 1.99) and β = −15.4 ± 2.9 to −16.9 ± 3.0% °C^{-1} (mean, −15.9% °C^{-1}), which is consistent with observational estimates.

The ensemble was rerun with the temperature increased by 1°C, and differences from the base simulations were used to estimate sensitivities. The delta-based β ranged from −7.8 to −12.2% °C^{-1} (mean, −9.3% °C^{-1}), which is consistent with higher-magnitude values from previous delta-based analyses (*2*, *10*) and lower than regression-based estimates. Simulations with precipitation perturbed by +1% each month yielded a delta-based α of 2.21 to 2.83 (mean, 2.52). It is not surprising that some previous delta estimates of β were as high as ours nor that some were lower, because models had a variety of features, with varying physical realism, differentially sensitizing their evapotranspiration to temperature, and the mechanisms underlying β generally were neither identified nor constrained with measurements.

We found that the difference between the model's regression- and delta-based sensitivities is explained by confounding variables: seasonal shifts of precipitation that historically accompanied annual anomalies of temperature. During warm water years, precipitation tended to shift from December–April to August–September. Because discharge sensitivity to precipitation is strong in winter (when extra precipitation tends to run off) (*3*) and weak in summer (when extra precipitation

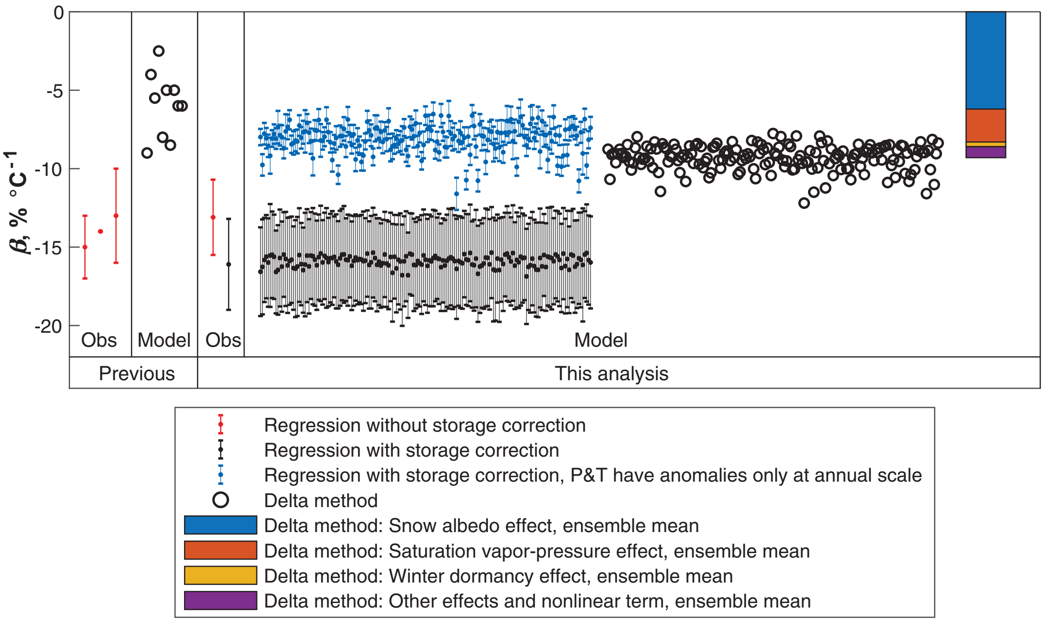


Fig. 4. Summary of estimates of β from previous studies and from this analysis. Left to right: previous observational (Obs) and model analyses (*2*, *4*, *6*–*10*) and results from this analysis. Error bars represent ± one standard error of estimation from the regressions. The multicolored bar shows the contribution of each of the temperature-sensitive mechanisms to the magnitude of β. Excluded as unrealistic from the previous delta analyses are cases in which maximum daily temperature was perturbed whereas minimum was not (*10*). The label "P&T have anomalies only at annual scale" refers to the computations in which the monthly course of precipitation in every year was set to climatology times a factor that preserved the observed annual anomaly.

tends to evaporate), runoff is suppressed during warm years. To remove the confounding variables from our comparison of the delta and regression estimates, we modified the original experiments so that the monthly course of precipitation in every year was set to climatology times a factor that preserved the observed annual anomaly; for temperature, the annual anomalies were applied as additive constants to the climatology. For these experiments, the models' regression-based α and β were α = 2.26 ± 0.03 to 3.00 ± 0.08 (mean, 2.59 ± 0.04) and β = −6.5 ± 0.7 to −11.6 ± 1.0% °C^{-1} (mean, −8.1 ± 0.7% °C^{-1}), which is in reasonable agreement with the delta-based values; the difference between −8.1 ± 0.7 and −9.3 is only marginally significant, and allowances must be made for the simple formulation of the storage correction for the regression estimate (*15*).

The substantial dependence of inferred sensitivities on seasonal distributions of climate perturbations implies that the use of simple annual sensitivity parameters (α and/or β) can severely distort climate-change analyses. This is a shortcoming of both the regression and delta approaches. With regression, the derived sensitivities depend on basin-specific historical intra-annual and interannual variability, including the confounding precipitation-temperature covariance. In the usual delta approach, the perturbations have no seasonal variations, and the roles of precipitation and temperature are decoupled, so delta sensitivities are more readily interpreted. However, the best approach for hydroclimatic projections is to use the delta approach with projected monthly varying climate changes.

To understand the ensemble-mean magnitude −9.3% °C^{-1} of the delta-based β and its potential relevance for ongoing anthropogenic climate change, we consider the physical processes at play. Temperature enters the model in four ways: (i) Because SWE depends on the phase of precipitation and the rate of snow melt, the surface albedo and, hence, the evaporative potential are temperature-dependent. (ii) The maximum fraction of net radiation that is converted to latent heat flux depends on the temperature-dependent slope of the saturation vapor-pressure curve (*11*, *16*). (iii) Evapotranspiration from soil ceases below a critical temperature, simulating winter dormancy of vegetation. (iv) Temperature affects the timing of snow melt and, thus, causes differences in sublimation and evapotranspiration in the model. By disabling these processes one at a time, we found that the contributions from the first three processes were −6.2, −2.1, and −0.3% °C^{-1}, respectively, and other snow-storage effects and nonlinear interactions accounted for the remainder. Figure 4 summarizes the foregoing reconciliation of sensitivity estimates.

We repeated the analysis under the assumption that a change in albedo induces negligible radiation feedbacks (Fig. 1B, red). We found an ensemble mean β of −7.8% °C^{-1}, indicating that our findings are somewhat sensitive to uncertainties in albedo-radiation feedback.

Unaccounted factors in our analysis include externally driven changes in radiation (e.g., from changing atmospheric composition), changes in boundary-layer entrainment (*17*), and stomatal responses to CO_2 fertilization (*18*). The latter two factors tend to decrease the efficiency of the conversion of net radiation to potential evapotranspiration. We found the potential net effect of these factors on β to be negligible (*15*).

Our parameterization of potential evapotranspiration by use of the Priestley-Taylor formulation (*16*), which allowed for no atmospheric aridity feedback caused by actual (nonpotential) evapotranspiration, could be questioned. We therefore repeated our analysis with allowance for this feedback (*15*), finding a negligible difference in results. Another caveat to consider is that our adoption of the Priestley-Taylor formulation, even when we consider the aridity feedback, implicitly assumes that variabilities (in particular, long-term trends) of wind speed and humidity will not affect the value of the Priestley-Taylor α, even though they do, on certain time scales, play a documented role in variabilities of pan evaporation (*19*) and of the American Society of Civil Engineers Standardized Reference Evapotranspiration (*20*).

How much have temperature changes contributed to the period-of-record discharge trend (−19.6 and −20.1% per century observed and modeled, respectively) and the 2000 to 2017 discharge deficit (−15.9 and −17.6% of previous mean observed and modeled, respectively)? If we set temperature every year to its climatology, the model yields a discharge trend of −8.4% per century and a discharge deficit of −8.1%. We conclude that temperature sensitivity accounts for more than half of both drying phenomena, which is consistent with a previous analysis (*21*).

What about the future? To characterize future temperature and precipitation, we used the 8 out of 24 Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models that simulated 1913 to 2017 discharge (area-weighted runoff) within a factor of two of the observed discharge. (The constraints used for climate-model selection were much less stringent than those used for selection of hydrologic model parameter sets because the hydrologic model was driven by historical climate time series, whereas the modeled climate time series were biased and independent of actual history.) From CMIP5's historical, Representative Concentration Pathway 4.5 (RCP4.5), and RCP8.5 scenarios, we computed month-of-year temperature climatology increases from 1913–2017 to 2036–2065, added them to the observed historical record, and reran the ensemble. Across the set of eight climate models, ensemble-mean discharge decreased 14 to 26% (RCP4.5) and 19 to 31% (RCP8.5).

Could possible future increases in precipitation counteract the temperature-driven drying? When month-of-year temperature increases and precipitation ratios from the climate models were both applied, the ensemble-mean discharge decreased 5 to 24% (RCP4.5); under RCP8.5, changes ranged from an increase of 3% to a decrease of 40%. Thus, it appears unlikely that precipitation changes will be sufficient to fully counter the temperature-induced drying, though they might moderate it.

Many water-stressed regions around the world depend on runoff from seasonally snow-covered mountains, and more than one-sixth of the global population relies on seasonal snow and glaciers for water supply (*22*). It has been well established that snowpack serves as a reservoir that beneficially regulates the timing of water availability (*23*). Our findings imply that snow cover is also a protective shield that limits radiation absorption by, and consequently evaporative losses from, this natural reservoir; incidentally, this explains the observed phenomenon of precipitation as snowfall favoring runoff (*24*). The progressive diminution of this ecosystem service as a result of climate change will have a deleterious effect on water availability in snow-fed regions that are already stressed, including the UCRB.

REFERENCES AND NOTES

1. T. James, A. Evans, E. Madly, C. Kelly, "The economic importance of the Colorado River to the basin region" (L. William Seidman Research Institute, Arizona State Univ., 2014); https://businessforwater.org/wp-content/uploads/2016/12/PTF-Final-121814.pdf.
2. G. J. McCabe, D. W. Wolock, *Geophys. Res. Lett.* **34**, L22708 (2007).
3. C. A. Woodhouse, G. T. Pederson, K. Morino, S. A. McAfee, G. J. McCabe, *Geophys. Res. Lett.* **43**, 2174–2181 (2016).
4. G. J. McCabe, D. M. Wolock, G. T. Pederson, C. A. Woodhouse, S. McAfee, *Earth Interact.* **21**, 1–14 (2017).
5. B. Udall, J. Overpeck, *Water Resour. Res.* **53**, 2404–2418 (2017).
6. J. A. Vano *et al*., *Bull. Am. Meteorol. Soc.* **95**, 59–78 (2014).
7. R. R. Revelle, P. E. Waggoner, in *Changing Climate: Report of the Carbon Dioxide Assessment Committee* (National Academy Press, 1983), pp. 418–432.
8. K. Nowak, M. Hoerling, B. Rajagopalan, E. Zagona, *J. Clim.* **25**, 4389–4403 (2012).
9. L. L. Nash, P. H. Gleick, "The Colorado River basin and climatic change: The sensitivity of streamflow and water supply variations to temperature and precipitation" (U.S. Environmental Protection Agency, EPA 230-R-93-009, 1993).
10. J. A. Vano, T. Das, D. P. Lettenmaier, *J. Hydrometeorol.* **13**, 932–949 (2012).
11. P. C. D. Milly, J. Kam, K. A. Dunne, *Water Resour. Res.* **54**, 2624–2641 (2018).
12. P. C. D. Milly *et al*., *Science* **319**, 573–574 (2008).
13. P. C. D. Milly, K. A. Dunne, *J. Am. Water Resour. Assoc.* **53**, 822–838 (2017).
14. F. G. Hall *et al*., in *Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System*, P. Kabat *et al*., Eds. (Springer, 2004), pp. 93–114.
15. Methods and supplementary text can be found in the supplementary materials.
16. C. H. B. Priestley, R. J. Taylor, *Mon. Weather Rev.* **100**, 81–92 (1972).
17. P. A. Dirmeyer, Y. Jin, B. Singh, X. Yan, *J. Hydrometeorol.* **14**, 829–849 (2013).
18. P. C. D. Milly, K. A. Dunne, *Nat. Clim. Chang.* **6**, 946–949 (2016).
19. M. L. Roderick, L. D. Rotstayn, G. D. Farquhar, M. T. Hobbins, *Geophys. Res. Lett.* **34**, L17403 (2007).
20. M. T. Hobbins, *Trans. Am. Soc. Ag. and Biol. Engineers* **59**, 561–576 (2016).
21. M. Xiao, B. Udall, D. P. Lettenmaier, *Water Resour. Res.* **54**, 6739–6756 (2018).
22. T. P. Barnett, J. C. Adam, D. P. Lettenmaier, *Nature* **438**, 303–309 (2005).
23. I. T. Stewart, D. R. Cayan, M. D. Dettinger, *Clim. Change* **62**, 217–232 (2004).
24. W. R. Berghuijs, R. A. Woods, M. Hrachowitz, *Nat. Clim. Chang.* **4**, 583–586 (2014).

ACKNOWLEDGMENTS

This study was facilitated by the Geophysical Fluid Dynamics Laboratory of the National Oceanic and Atmospheric Administration and by several data providers cited in the supplementary materials. The authors gratefully acknowledge colleague reviews by R. Koster and T. Delworth. **Funding:** The authors are supported by the U.S. Geological Survey. **Author contributions:** P.C.D.M. was responsible for the conceptualization and overall direction of the work and wrote the original draft. P.C.D.M. and K.A.D. carried out computations. K.A.D. performed data curation and reviewed the original draft. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** No original data collection was performed. The results of this study are reproducible and extensible by use of the cited data sources and other information in the supplementary materials.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/367/6483/1252/suppl/DC1
Materials and Methods
Supplementary Text
Fig. S1
Tables S1 to S5
References (*25*–*32*)
Data S1 to S3

24 August 2019; accepted 4 February 2020
Published online 20 February 2020
10.1126/science.aay9187

Science

Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation

P. C. D. Milly and K. A. Dunne

Science **367** (6483), 1252-1255.
DOI: 10.1126/science.aay9187originally published online February 20, 2020

Evaporating futures

Drought and warming have been shrinking Colorado River flow for many years. Milly and Dunne used a hydrologic model and historical observations to show that this decrease is due mainly to increased evapotranspiration caused by a reduction of albedo from snow loss and the associated rise in the absorption of solar radiation (see the Perspective by Hobbins and Barsugli). This drying will be greater than the projected precipitation increases expected from climate warming, increasing the risk of severe water shortages in an already vulnerable region.

Science, this issue p. 1252; see also p. 1192

WATER DESK

Who should pay for water conservation in the West? Water managers wade into discussion

By **Heather Sackett** December 30, 2019

COURTESY PHOTO

Seen from the air, Glen Canyon Dam holds back the Colorado River to form Lake Powell. The state of Colorado is looking into how to fund a program that would pay irrigators to reduce their consumptive use in order to send water downstream to a savings account in Lake Powell.

LAS VEGAS — Water managers from throughout the Colorado River Basin took the stage at the Colorado River Water Users Association conference earlier this month to talk about conserving water in the face of the twin threats to the river: increasing demand and climate change.

The state of Colorado is currently exploring a water-use-reduction program that is largely designed to pay farmers and ranchers on the Western Slope to voluntarily conserve water. While there's still debate whether such a program should be implemented, the first question many ask is how to pay for such a program. In recent months, some water managers have come up with innovative ways to fund the controversial water-use-reduction plan — known as demand management — that wouldn't rely entirely on taxpayers.

The drought contingency plan, which water leaders inked at last year's annual CRWUA meeting, set up a reserve account of 500,000 acre-feet of water that the Upper Basin — Colorado, Wyoming, Utah and New Mexico — could use to store water in Lake Powell as an insurance policy against dwindling reservoir levels.

In November, Colorado voters passed Proposition DD, which is projected to funnel roughly $16 million a year to the Colorado Water Conservation Board, or CWCB, by taxing sports betting. Demand management is one of the two things money from Proposition DD could fund (the other is Water Plan grants).

However, it's widely accepted that $16 million is not enough to fund either of those things in their entirety. Demand management needs other sources of money.

Although the Glenwood Springs-based Colorado River Water Conservation District still isn't convinced that a demand-management program is the right approach for the Western Slope, general manager Andy Mueller told the Las Vegas crowd that the Upper Basin has to reduce its water consumption — and explore creative solutions to accomplish that.

"I often talk about the Lower Basin overuse and how that's driving the problem, and I will say they in the Lower Basin need to fix that problem," Mueller said. "I will also say we in the Upper Basin … need to reduce our use. The science is pretty clear. Water we all thought was there even 15 years ago is not going be there. You can't have water for the environment and the people if we are not reducing consumptive use throughout the basin."

Brent Gardner-Smith/Aspen Journalism

General Manager of the Colorado River Water Conservation District Andy Mueller speaks at the district's annual seminar in 2018. Mueller told the audience the Upper Basin needs to reduce its consumptive use at the Colorado River Water Users Association conference in Las Vegas earlier this month.

Who should pay?

So, if nearly all water users on the Colorado River, including those in the Lower Basin — California, Nevada and Arizona — would stand to benefit from a demand-management program, who should pay for it?

Not Colorado taxpayers, Mueller said, at least not entirely.

"Eighty million (dollars) a year would need to be out there in payments to get the appropriate amount of water in Lake Powell," he said. "That cost to taxpayers is too high. So you turn to: Who else benefits from us creating a storage account in Lake Powell?"

One answer: power providers in both the Upper and Lower Basin states, who all need Lake Powell to remain above 3,525 feet, the minimum level required to continue generating hydropower.

For example, the Western Area Power Administration sells hydropower generated at Glen Canyon Dam and other federal dams along the Colorado River to local communities, including Aspen and Glenwood Springs. In all, WAPA sells hydropower from the Colorado River system to about 200 customers, including municipalities, rural electric cooperatives, federal and state agencies, irrigation districts and Native American tribes.

Mueller thinks adding a small demand-management surcharge to customers' bills is something that should be explored,

"Power customers should share in the costs of us storing for demand management," he said.

Another potential source of funds could be nonprofit environmental groups, since sending more water downstream to Lake Powell would also benefit stream health. The federal government, whose Bureau of Reclamation operates Lake Powell and Lake Mead, also has a role to play, Mueller said.

But no matter where the money comes from, Mueller said it must be channeled through the CWCB in a heavily regulated market to prevent speculation by private buyers.

"We have been very clear it needs to be a guided market if it's going to happen, with lots of thoughtful, proactive rules to prevent lots of serious consequences," he said.

Brent Gardner-Smith/Aspen Journalism

This field in lower Woody Creek is irrigated with water that eventually flows into the Colorado River. The state of Colorado is exploring how to fund a program that would pay irrigators to reduce their consumptive use in order to send water downstream to a savings account in Lake Powell.

State-led exploration

The CWCB currently has a workgroup devoted to exploring how to fund demand management. The group has met twice so far, but CWCB facilitator Anna Mauss said the two biggest questions the group is grappling with are these: how much water is needed and what would the cost be. The workgroup, she said, will dive deeper into funding strategies at the next meeting, scheduled for the end of January.

"We are baby-stepping into this, trying to be diligent," Mauss said. "It's really just looking at scenarios at this point."

The state is also encouraging innovative ideas from the private sector. The CWCB recently awarded $72,000 to 10.10.10, a Colorado Nonprofit Development Center project that aims to tackle "wicked problems" in water and climate. Under the program, 10 entrepreneurs will, over 10 days, attempt to tackle 10 systemic issues that are not adequately addressed by government, organizations or institutions.

"Yes, we are looking at demand management, and it could be one of the wicked problems we address," said Jeffrey Nathanson, president of 10.10.10.

Brent Gardner-Smith/Aspen Journalism

Water from the Colorado River irrigates farmland in the Grand Valley. The state of Colorado is looking into how to fund a program that would pay irrigators to reduce their consumptive use in order to send water downstream to a savings account in Lake Powell.

Platform for payment?

While some people work on finding sources of funding, others are already creating a platform to pay irrigators once the money is in place. Southwest Colorado water managers Steven Ruddell and David Stiller think a reverse auction to compensate water users for using less is the best way to go.

A reverse auction, which features many sellers (farmers and ranchers) and one buyer (the state of Colorado through the CWCB), would allow water-rights holders to set the lowest price they are willing to accept to voluntarily send their water downstream. According to Ruddell and Stiller's paper on the subject, a reverse auction would remove paying for demand management from a political process and move it into a market-based process that lets water-rights holders bid the fair-market value of their water. It would also keep costs down for the CWCB.

Ruddell and Stiller presented their reverse-auction idea at the Upper Colorado River Basin Forum at Colorado Mesa University last month.

"We've tried to bite off a small piece of demand management by suggesting we use an auction that people are familiar with," Ruddell said. "It's used to determine the value of something, especially in the ag world."

There are still many questions surrounding how a demand-management program might be paid for.

"There are all sorts of options," Mueller said. "We shouldn't just focus on raising taxes in our state."

Aspen Journalism collaborates with The Aspen Times and other Swift Communications newspapers on coverage of water and rivers. This story appeared in the Dec. 30 edition (https://www.aspentimes.com/news/local/who-should-pay-for-water-conservation-in-the-west-water-managers-wade-into-discussion/) of The Aspen Times.

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*, 6739–6756. https://doi.org/10.1029/2018WR023153

Received 17 APR 2018
Accepted 22 AUG 2018
Accepted article online 30 AUG 2018
Published online 22 SEP 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 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.

10.1029/2018WR023153

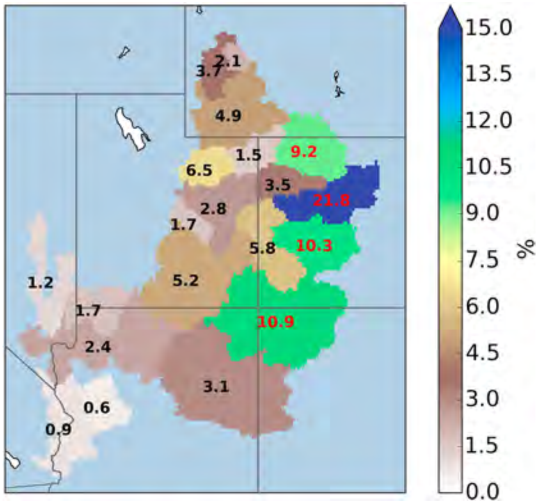


Figure 1. Percent of total CRB runoff (at Imperial Dam) originating from 20 subbasins, calculated based on long-term average from VIC simulation for water years 1971–2014. The subbasins shown in Figure 1 were extracted from a published data set by Wu et al. (2012).

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

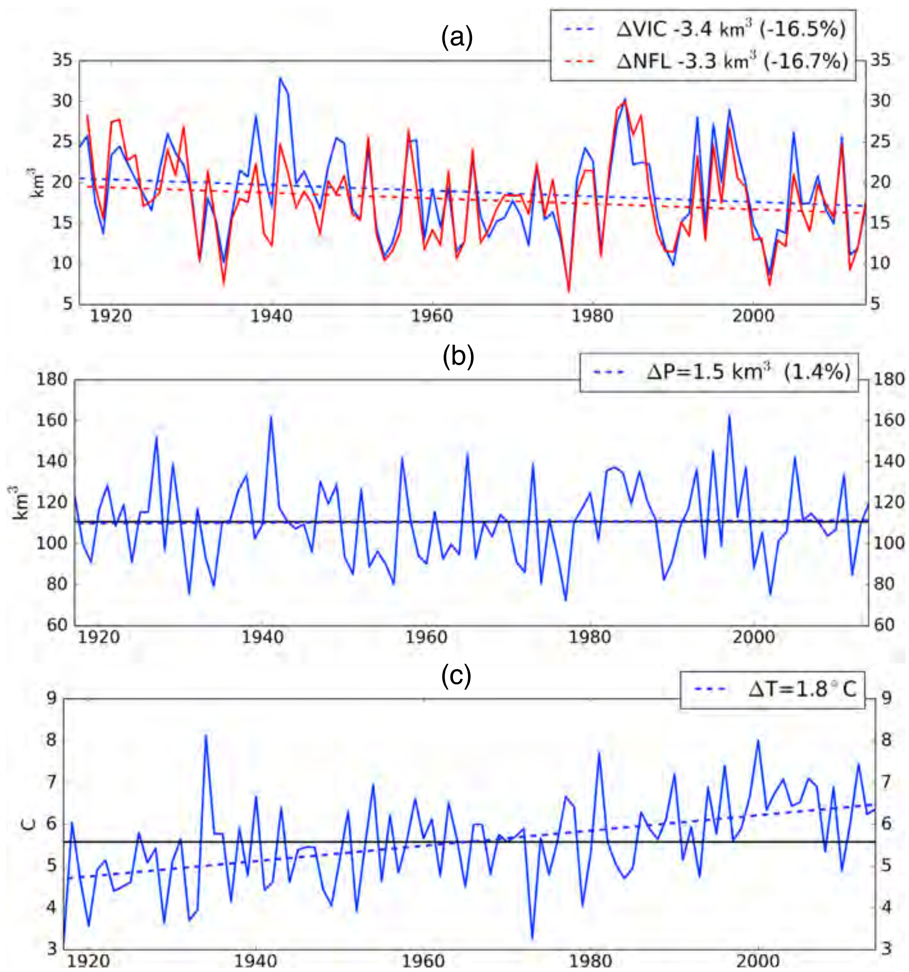


Figure 2. Annual time series and linear regression trend plots for Colorado River Basin above Lees Ferry: (a) annual (naturalized) runoff, (b) annual precipitation, and (c) annual average surface temperature calculated by VIC. Changes are calculated relative to the starting value of the fit. Note that 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

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.

10.1029/2018WR023153

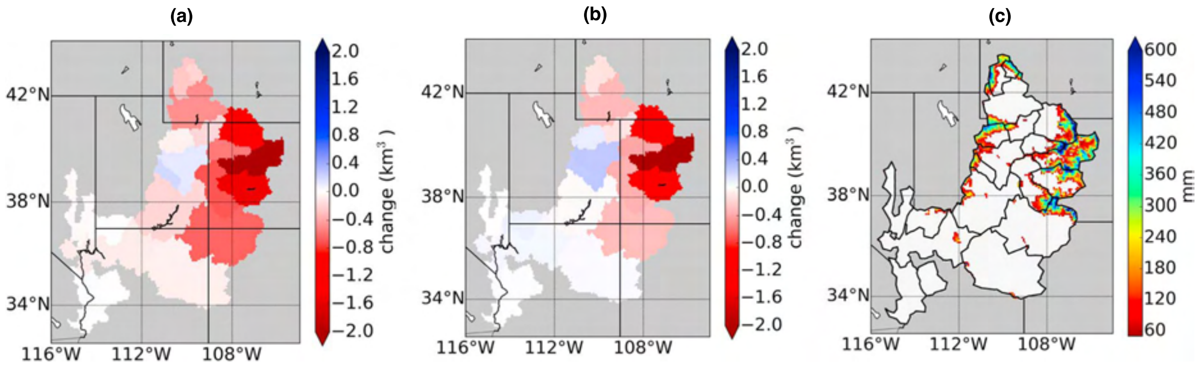


Figure 3. Spatial plots of 1 April SWE trends for (a) baseline simulation and (b) T-detrend simulation over each subbasin. The changes over 1916–2014 are calculated relative to starting value of the linear regressions. (c) Long-term average 1 April SWE.

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

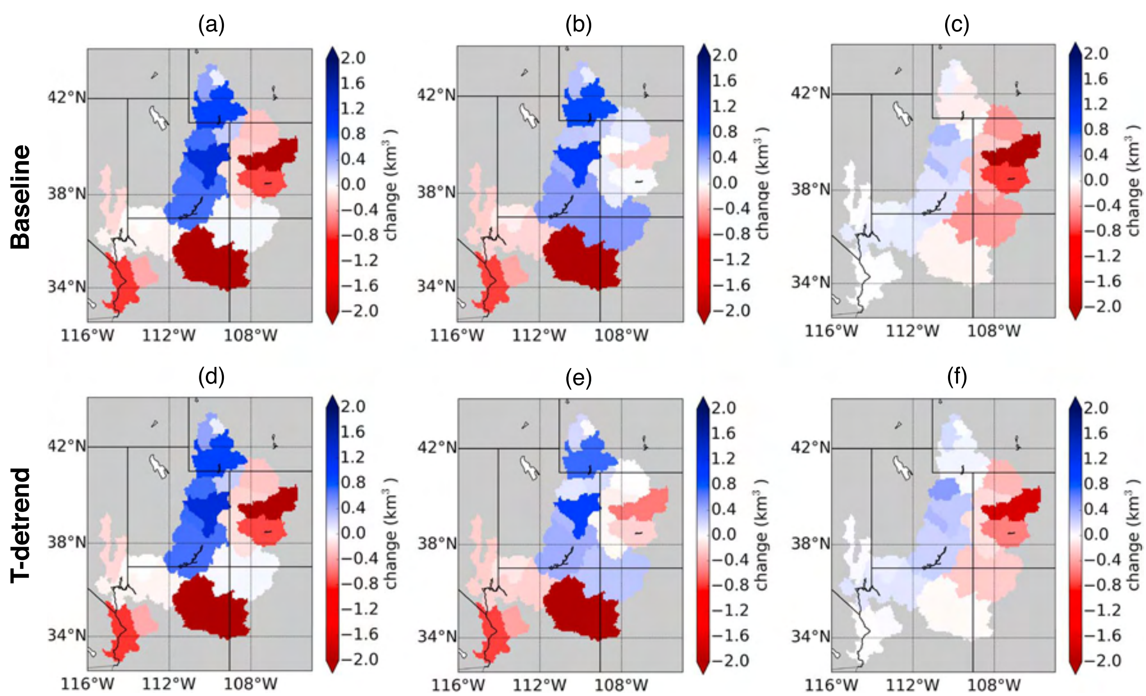


Figure 4. Spatial changes of (a) annual precipitation from gridded observations, (b) ET, and (c) runoff from baseline VIC simulation over 1916–2014 for CRB above Imperial Dam. Changes are calculated relative to the starting value of linear fits. Panels (d)–(f) are the same as (a)–(c), but variables are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

10.1029/2018WR023153

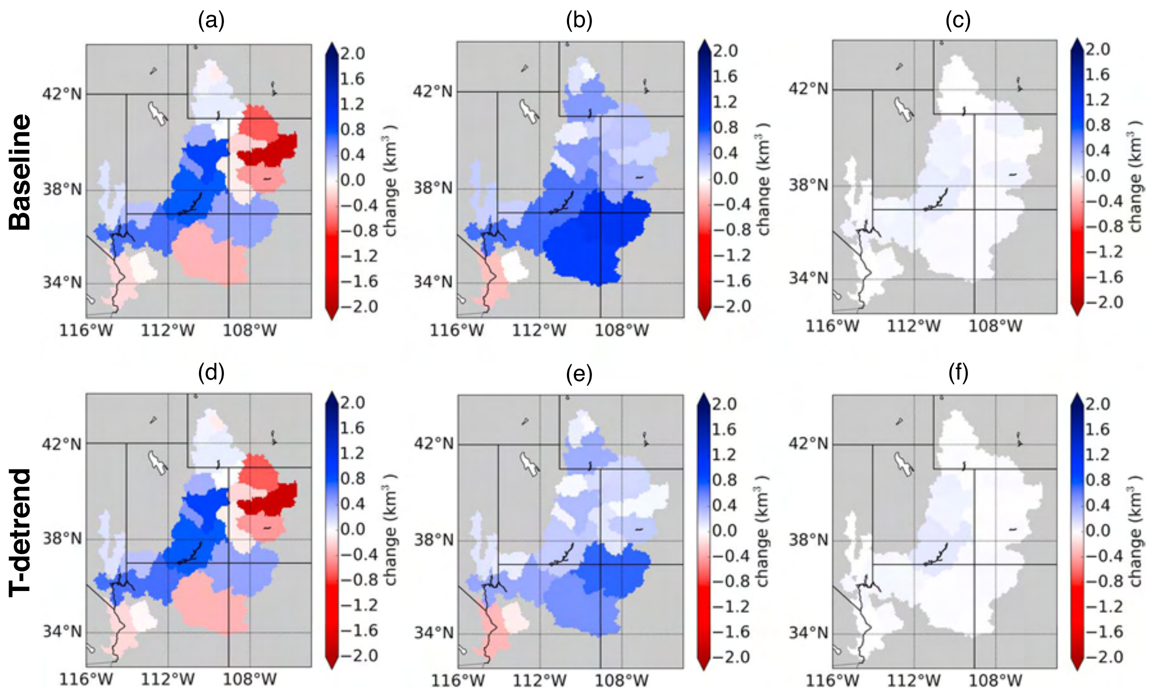


Figure 5. Same as Figure 4 but for winter (October–March).

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

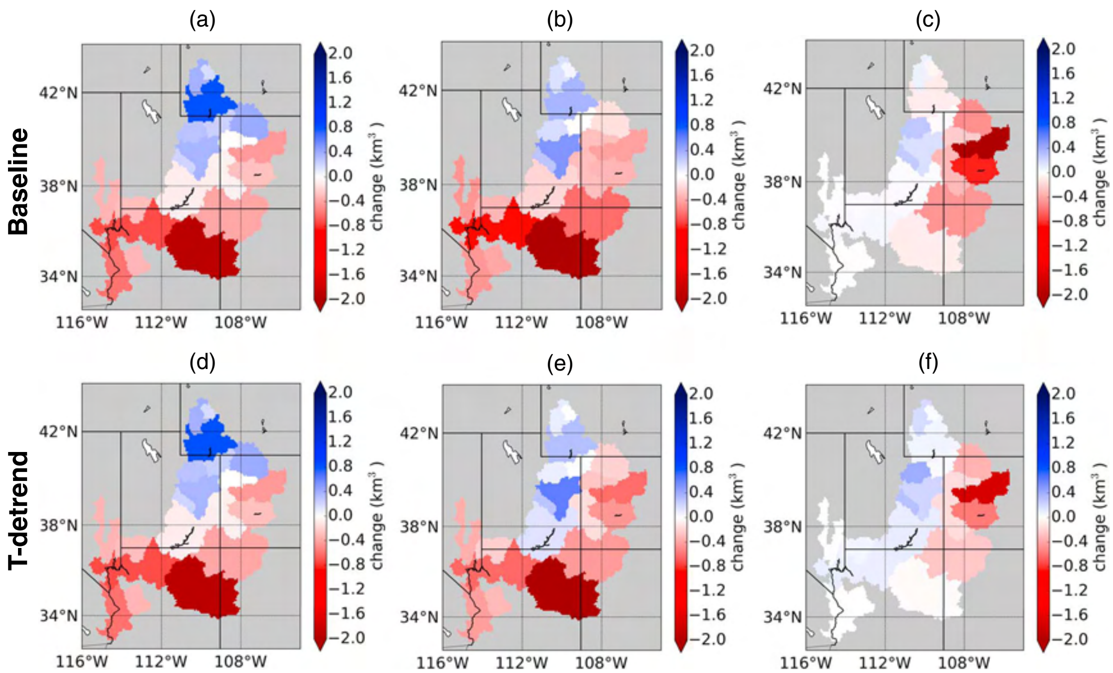


Figure 6. Same as Figure 4 but for summer (April–September).

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.

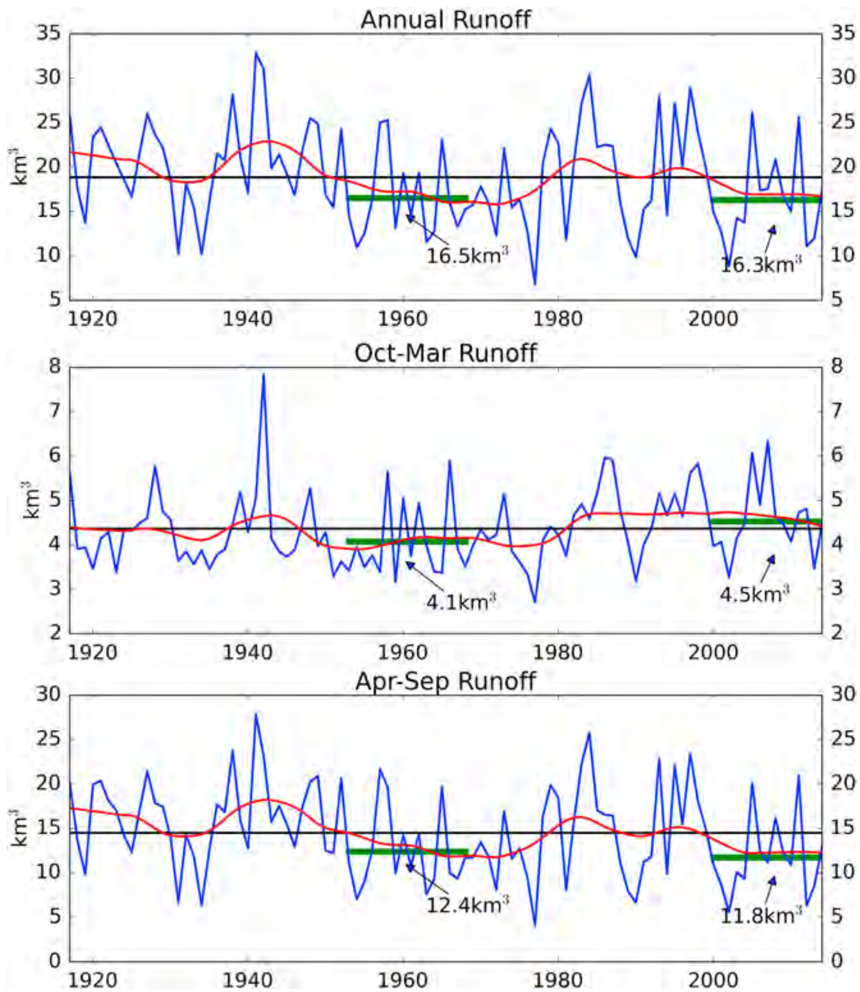


Figure 7. Time series of VIC simulations of annual runoff (top), winter runoff (middle), and summer runoff (bottom) at Lees Ferry (UCRB). The black horizontal lines are the long-term means, and red lines result from LOWESS filtering of VIC results.

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.

10.1029/2018WR023153

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.

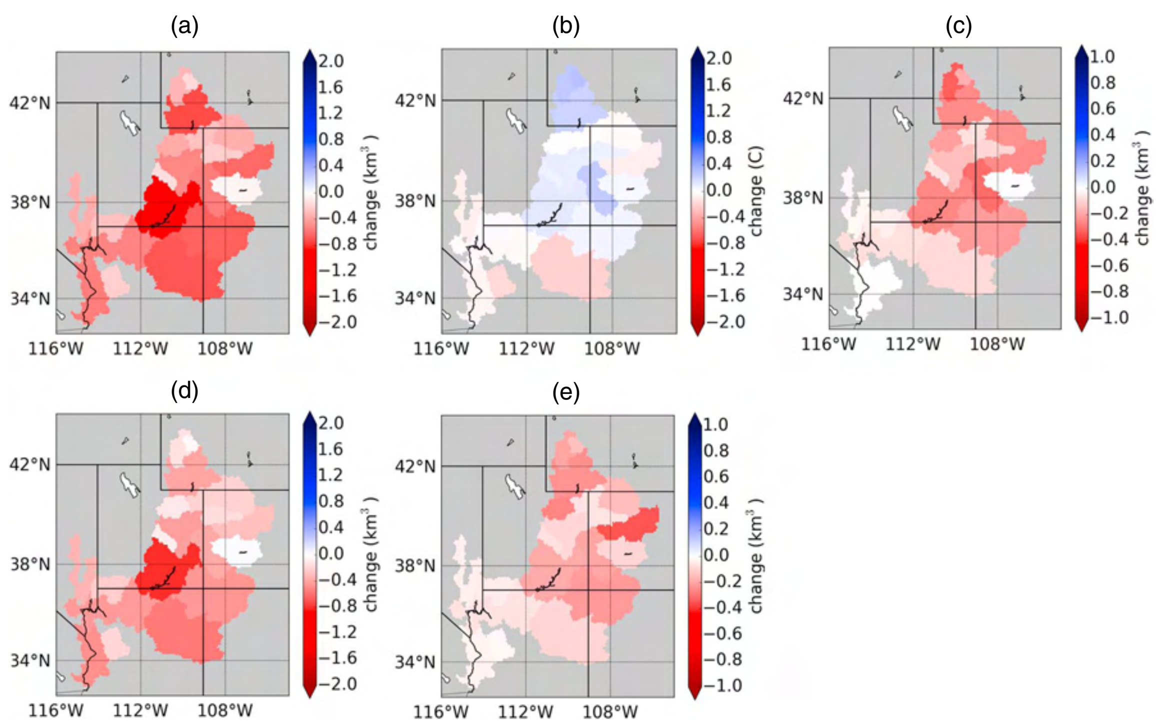


Figure 8. Average annual anomaly plots for each subbasin during the drought period 1953–1968. The variables in each panel are (a) precipitation, (b) temperature,(c) SWE, (d) ET, and (e) runoff (panels (c)–(e) are from VIC simulations).

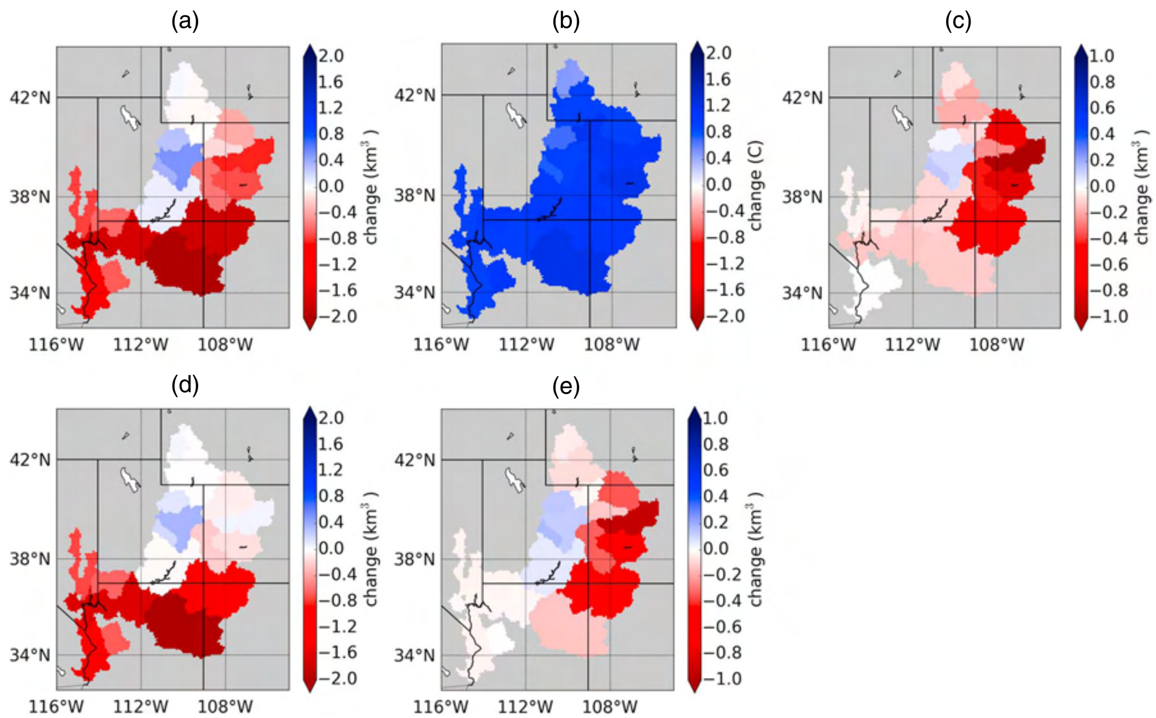


Figure 9. Same as Figure 8 but for 2000–2014 Millennium Drought.

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 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.

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 $\Delta P/P$ 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.

10.1029/2018WR023153

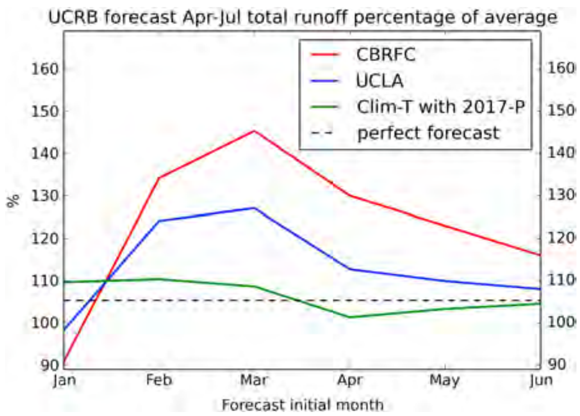


Figure 10. April–July 2017 streamflow forecasts at Lees Ferry initialized on the first day of each month expressed as percentages relative to 1981–2010 climatology. Red line represents the official forecasts published by CBRFC; blue line represents equivalent VIC reforecasts; green line is forecast with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

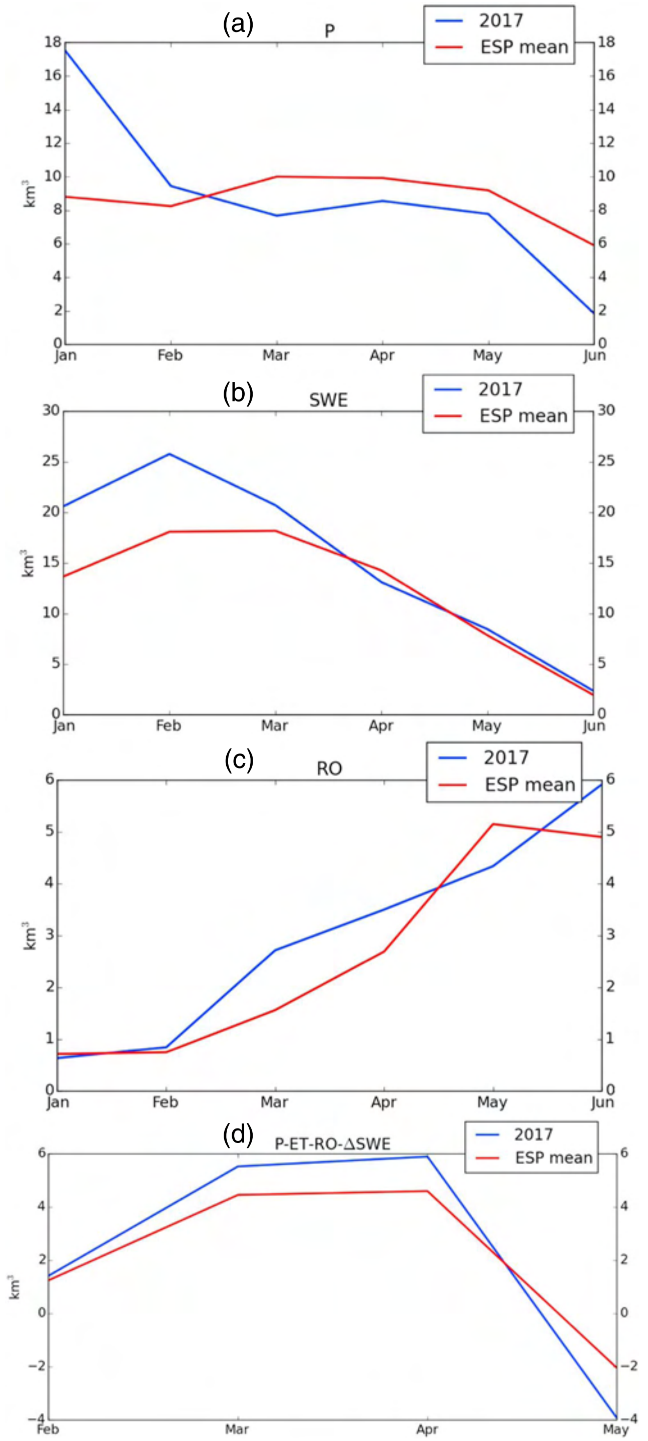


Figure 11. Monthly time series plots of (a) precipitation, (b) SWE, (c) runoff, and (d) soil moisture change. The blue line is the 2017 forecast; red line is historical climatology.

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

(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.

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

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

How Long Does a 15-Year Drought Last? On the Correlation of Rare Events

GEORGE RHEE AND JIMMY SALAZAR

Department of Physics and Astronomy, University of Nevada, Las Vegas, Las Vegas, Nevada

CORWIN GRIGG

Department of Mechanical Engineering, University of Nevada, Las Vegas, Las Vegas, Nevada

(Manuscript received 7 June 2018, in final form 18 October 2018)

ABSTRACT

Communities reliant upon the Colorado River system are at risk of water shortages because of fluctuations of the river's streamflows. The solution to the water supply problem for the Colorado River system lies within a quantitative understanding of these fluctuations during droughts. Streamflow data (direct and inferred) for the Colorado River extend back approximately 1200 years through the analysis of tree-ring records (Meko et al.; Woodhouse et al.). We further analyze these data using a mathematical model to present estimates for the future water supply of the Colorado River by comparing measured streamflows of the past century with the yearly tree-ring data of the Colorado River. We estimate that the Colorado River system's reservoirs lack enough stored water reserves to last through the current drought, which has been ongoing since 2000. If true, it is essential to reevaluate the way water is used and stored for the Colorado River. The methods presented are relevant to any river system whose streamflow statistics are Gaussian.

1. Introduction

Approximately 40 million people in seven western U.S. states rely upon the Colorado River for their water supply. The current drought, defined as a prolonged period of abnormally low streamflow resulting in a shortage of water, makes meeting water demands in these areas a problem. This has caused a mismatch between water supply and demand over the last 19 years. As a result, Lake Mead and Lake Powell have both seen substantial decreases in their water storage. This contributes to a substantial amount of economic loss; studies have shown that the Unites States has paid over 200 billion U.S. dollars (USD) in costs due to droughts since 1980 (Smith and Katz 2013). An overview of the Colorado River basin storage, natural streamflows, precipitation, and temperature changes since ~1900 is given in Udall and Overpeck (2017) (see also USBR 2011 for more details).

The droughts we address are hydrological droughts. In this paper, we define a drought as a time interval when the mean yearly natural streamflow of the Colorado River falls below the long-term mean. For example, for the past 15 years, the mean streamflow was 12 million acre-feet yr^{-1}, but for the twentieth century, the mean streamflow was 15 million acre-feet yr^{-1}. Given that the root-mean-square (RMS) of the 15-yr-averaged streamflows is 2 million acre-feet yr^{-1}, we consider the current drought to be a 1.5σ event.

The ability of scientists to predict droughts far enough in advance can provide policy makers with ample time to take appropriate measures. Current modeling techniques are unable to do this (Vano et al. 2014), although short-term predictions can be made regarding the strength and length of future droughts. A comprehensive study undertaken by the Bureau of Reclamation (USBR 2011) discusses various methods currently used to predict the future streamflows of the Colorado River. One of these, the Paleo Reconditioned Scenario, is most relevant to this paper and is briefly explained below. For an up-to-date review regarding drought prediction and climate change, see Cook et al. (2018).

The Paleo Reconditioned Scenario (Prairie et al. 2008), also known as the Parametric Paleo Conditioning Method, analyzes the length of dry and wet periods in the paleo record. These are derived from 5-yr running means of streamflow reconstructions at Lees Ferry, Arizona, which serves as the boundary between the upper and lower

Corresponding author: George Rhee, grhee@physics.unlv.edu

DOI: 10.1175/JCLI-D-18-0326.1

basins of the Colorado River. The streamflow magnitudes are generated by conditionally choosing from a wet or dry sequence corresponding to the type of sequence derived from the paleo record. A drawback of this method is that magnitudes not recorded in the observed gauged records cannot be generated. However, the method has the advantage of reproducing deficit and surplus periods more extended than those seen in the measured streamflow data.

We present a variant of the Paleo Reconditioned Scenario to estimate natural streamflows for the next few years of the Colorado River at Lees Ferry. The method uses a combination of direct streamflow measurements, together with a statistical measure of the paleo reconstructed data. For any system of Gaussian fluctuations, the correlation properties of fluctuations in known amplitude and scale can be estimated (Ault et al. 2013; Sivia and Skilling 2006; Rasmussen and Williams 2006). A drought can be defined with respect to several different variables such as streamflow, rainfall, reservoir levels, and soil moisture. This paper uses streamflow of the Colorado River at Lees Ferry to measure drought. The results should be viewed as a lower limit of future drought since climatic conditions are predicted to worsen in both magnitude and frequency because of a changing climate (Solomon et al. 2009; Strzepek et al. 2010; USBR 2011; Vano et al. 2014; Cook et al. 2015; Prein et al. 2016). For reviews and discussion of research on clustering of extreme events and long-term memory as they pertain to climate, precipitation, and river flow, see Bunde et al. (2005) and Bunde et al. (2012).

The present study is a statistical exercise in inference. Another approach is to look at physical processes when studying the Colorado River streamflows. The effects of El Niño–Southern Oscillation (ENSO), the Pacific decadal oscillation (PDO), and the Atlantic multidecadal oscillation (AMO) have been studied by various authors as they pertain to Colorado river streamflow (Nowak et al. 2012; Hidalgo and Dracup 2003; Redmond and Koch 1991). The results show that ENSO effects are more pronounced in the lower Colorado basin than the upper Colorado basin. A study by the National Research Council (2007) concludes that ENSO does not greatly affect the mountain headwater regions where the streamflows originate, so its effects are not likely to greatly improve upper-basin streamflow forecasts.

The effects of the PDO on Colorado River streamflows have also been examined. Although statistical relationships have been found, they manifest themselves in the lower basin. The physical mechanisms that lead to these effects are not currently understood. It has been shown that when the North Atlantic is warm for a decade or longer, streamflow in the upper Colorado River tends to be lower than average, and vice versa (Gray et al. 2004; McCabe et al. 2004). Again, no clear physical mechanism as to why this should be the case has been identified.

Switanek and Troch (2011) have used AMO and PDO time series to forecast streamflow anomalies in the upper Colorado River at Lees Ferry. They found correlations in the instrumental record, but not in the tree-ring record. They conclude that it remains uncertain whether reliable decadal streamflow predictions will be possible in the years ahead. These authors urge caution when interpreting results derived using AMO/PDO time series. These ENSO/AMO/PDO effects are present but are not well enough understood to have predictive value.

There is one clear correlation between physical variables that stands out. McCabe et al. (2017) show a strong inverse correlation ($r \sim -0.9$) between the 10-yr moving-average Z scores of runoff efficiency and water-year temperature (see their Fig. 3). What is also striking is that the correlation is stronger at the high temperature end. McCabe et al. (2017) present evidence that warm-season temperatures have a larger effect on streamflow relative to cool-season temperature. They predict that as warming continues, the negative effects of temperature on upper Colorado River basin streamflow will become more evident.

Xiao et al. (2018) have used the Variable Infiltration Capacity (VIC) hydrology model to run a simulation forced by gridded observations, and then a simulation in which the long-term temperature trend is removed from the model forcing. The goal is to see what effect warming has on streamflows. The streamflow data, when compared with the VIC simulations, are in reasonable agreement (see their Fig. 2). They conclude that higher temperatures have played a large role in the post-millennium drought. This model, while useful for identifying physical causes of the current drought, is not useful as a strictly predictive tool because one has to force the model with the known temperature and precipitation data to recover the past streamflows. The problem is that we cannot reliably predict the temperature and precipitation in the upper Colorado River basin from one year to the next. The model is important in that it highlights the vulnerability of the system to increases in temperature, which will most likely continue in the coming decades. Physical modeling is very important, but more work needs to be done to turn these models into useful tools for predicting the Colorado River streamflows.

2. The data

The streamflow data we use are the Bureau of Reclamation's natural streamflow computations for the Lees Ferry gauging station (USBR 2015). These data

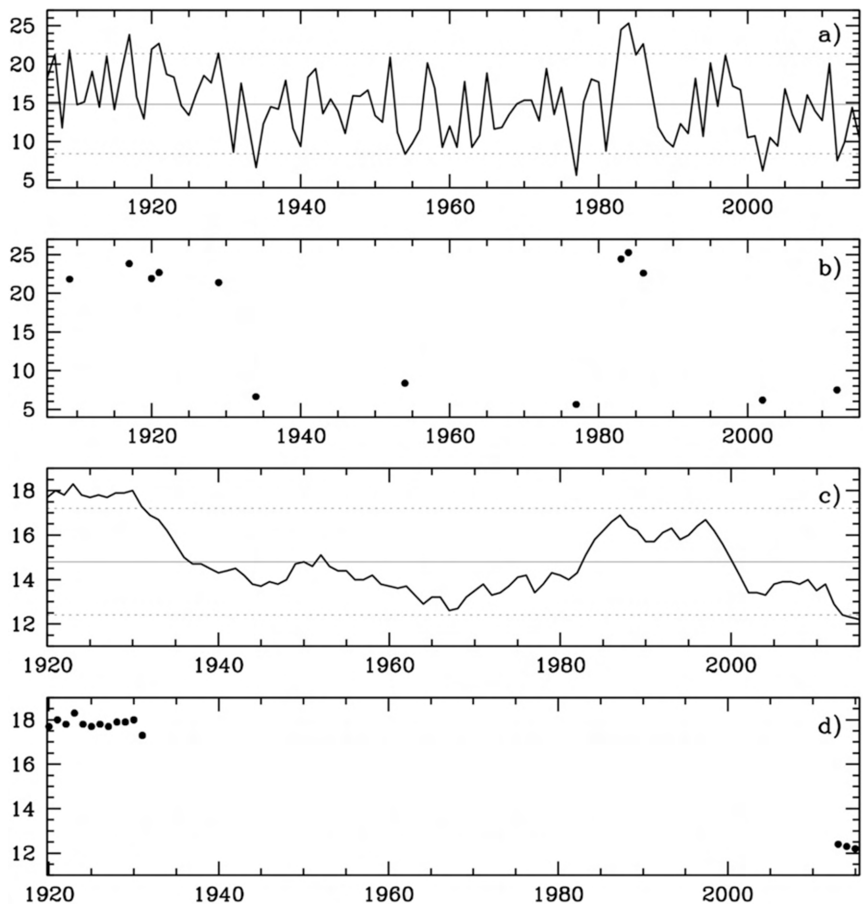


FIG. 1. Observed historical record for the natural streamflow of the Colorado River at Lees Ferry, Arizona (USBR 2015). (a) The entire observed historical record from 1906 to 2015. (b) Years in which the streamflow deviated by more than 7 million acre-feet (1.5σ) from the mean. (c) As in (a), but for a 15-yr running mean. The solid line corresponds to the mean streamflow of 14.9 million acre-feet yr^{-1}. The dotted lines show a deviation of 2 million acre-feet ($\pm$1.5σ) from the mean. (d) As in (b), but for a 15-yr running mean. The 15-yr period from 2001 to 2015 was the lowest in the observed historical record. Note the clustering of the data. All the points above and below the mean by 1.5σ are next to each other.

have the effects of diversions, depletions, and reservoir operations removed. Years are organized by water year, the period from October to September that best captures the annual snow season. Approximately 85% of all inflows occur above Lees Ferry (Christensen and Lettenmaier 2007). Direct measurements of the Colorado River's streamflows have only been available for a little more than a century.

We also use streamflows inferred from tree-ring data. Over 1000 years of tree-ring data for the Colorado River exist. These tree rings were measured at various locations where precipitation flows into the Colorado River. These data are directly related not just to precipitation, but also temperature, which in turn are related to the river's streamflows (Cook et al. 1995, 2004; Woodhouse et al. 2006; Meko et al. 2007).

Streamflows are measured in million acre-feet, which is a commonly used unit of volume in reference to large bodies of water. Figure 1a shows the yearly measured natural streamflows at Lees Ferry for the years 1906 to 2015. Figure 1b shows the years in which the streamflow deviated by more than 7 million acre-feet (1.5σ), from a mean of 14.9 million acre-feet. Although no conclusions can be drawn from Fig. 1b alone, a pattern does become apparent once the data are smoothed with a 15-yr running average (Figs. 1c and 1d).

The smoothed data reveal three years in which streamflow dropped below the 15-yr running mean to below 13 million acre-feet: 2012, 2013, and 2014. All three of these not only happened consecutively, but also occurred within the current decade. On the other end of the spectrum, something similar occurs with the 12 years

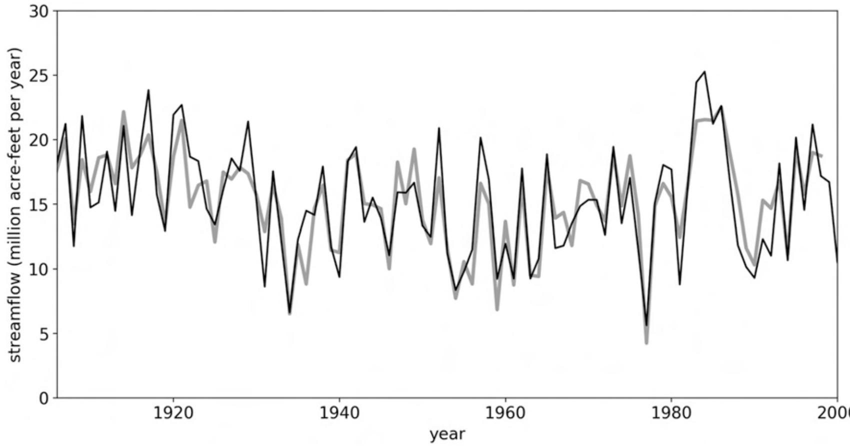


FIG. 2. Comparison of observed and reconstructed streamflow using data from Woodhouse et al. (2006). Reconstructed flows based on tree-ring data are shown with the gray line, and Lees Ferry gauge data are shown with the black line.

of data exceeding 17 million acre-feet yr^{-1}. All 12 years occur consecutively from 1920 to 1931. These data suggest that periods where the 15-yr mean streamflow exceeded or fell below a threshold of 1.5σ were clustered. In other words, it appears droughts may occur in groups.

This clustering of below-average and above-average years can have a drastic effect on the amount of water storage needed to last through a drought. This is particularly important since the Colorado River's reservoirs can only store about 4 times the annual streamflow, which tree-ring data suggest is inadequate. For example, a 15-yr below-average period could see a cumulative water deficit of approximately 30 million acre-feet of water. Two such consecutive periods can see a deficit upward of 60 million acre-feet of water, or the equivalent of the entire storage capacity of the Colorado River system. It is therefore imperative to determine the likelihood of such a scenario occurring.

Figure 1c illustrates the drawbacks of using too short a period of time to determine a baseline for the natural streamflow of the Colorado River. The streamflow in the first three decades of the twentieth century, when the Colorado River was measured for its baseline, were clearly higher than subsequent streamflows. Since the streamflow data were essentially chosen without regard to historical streamflows to characterize future streamflows, the data could easily be off by 2 million-acre feet of water or more. This would also result in an underestimation of the RMS variability of the system. There is now over a century of directly measured data of the Colorado River's streamflows, which could be used to establish a new baseline for the river. However, these data alone are insufficient to assess the current drought. The key lies within indirect samples of the streamflow over a much larger period of time.

Comparison of the directly and indirectly measured data suggests that the tree rings can be used to reliably estimate streamflows going back several centuries (Woodhouse et al. 2006). Figure 2 shows a comparison of the direct streamflow measurements and those inferred from the tree-ring data. Through careful analysis of this record, it is possible to characterize the nature of streamflow fluctuations on the multidecadal time scales pertinent to the current drought (Ault et al. 2013).

3. Model parameters and their estimation

To estimate the length of the drought currently affecting the Colorado River, six parameters from the paleo reconstructed and streamflow data must be measured. These parameters are μ, the mean streamflow; σ, the RMS deviations from the mean; t_d, the time scale for the drought; σ_{t_d}, the RMS deviations in the streamflows smoothed on a time scale of t_d; ν_d, the depth of the drought; and β, the slope of the power spectrum of the fluctuations. This section explains how all six parameters are obtained.

The first parameter μ is found by analyzing the long-term mean annual streamflow of the Colorado River from direct streamflow measurements and tree-ring records. The mean natural streamflow at Lees Ferry from 2001 to 2015 was approximately 12 million acre-feet yr^{-1} (USBR 2015), and approximately 15 million acre-feet yr^{-1} from 1906 to 2004 (Meko et al. 2007). In comparison, tree-ring data suggest that the long-term (from 762 to 2005) mean streamflow is approximately 14.6 million acre-feet yr^{-1}(Meko et al. 2012).

The value adopted for the mean streamflow influences the results presented here since it determines the extent of the current drought affecting the Colorado River. For example, the average streamflow for the decade of 1910 to 1920 was approximately 17.5 million acre-feet yr^{-1}. This was the largest streamflow decade in the last 1200 years. If one were to adopt the value of 17.5 million acre-feet as the long-term streamflow value for the Colorado River, one would erroneously classify all other years from 762 to 2015 as being in a state of drought.

The period from 1910 to 1920 illustrates the necessity of estimating the error in the mean. A lower limit on the uncertainty in the mean can be computed using Gaussian statistics where the error in the mean is the RMS value divided by the square root of the number of measurements (Sivia and Skilling 2006). The RMS value for the period from 1910 to 1920 is approximately 3.5 million acre-feet yr^{-1}. Therefore, the mean estimate should have been stated as $\mu = 17.5 \pm 1$ million acre-feet yr^{-1}.

The 3σ error is thus 3 million acre-feet yr^{-1}, meaning that one could assert in 1920 with more than 99% confidence that the mean streamflow value lay somewhere between 14.5 and 20.5 million acre-feet yr^{-1} based on the streamflows of the previous decade. This suggests that streamflow uncertainties were underestimated in 1922 when the Colorado River Compact was agreed upon and water was allocated among the Colorado River basin states. As a result, there was a high likelihood water would not be available in the long term when the agreement was signed.

The same reasoning applies to estimating the RMS scatter. Direct streamflow measurements yield an RMS scatter of approximately 4.5 million acre-feet yr^{-1}, a larger value than that inferred for the period from 1910 to 1920. Based on those 11 years of data, the RMS value is 3.5 million acre-feet yr^{-1} with an error of 2.3 million acre-feet yr^{-1}. This study utilizes the values for the mean and RMS streamflows derived from the direct streamflow measurement: $\mu = 15 \pm 0.4$ million acre-feet yr^{-1} and $\sigma = 4.5 \pm 0.3$ million acre-feet yr^{-1}. This σ value is an underestimation since it does not capture the variability on time scales longer than the 110-yr period for which we have reliable direct measurements.

The next two parameters t_d and ν_d are used to define the drought. In this paper, we use a t_d value of 15 years (i.e., a drought length of 15 years), although it is important to note the current drought in the Colorado River has now been ongoing for approximately 19 years. To estimate the depth of the drought ν_d, we use $\sigma_{15} = 2 \pm 0.8$ million acre-feet yr^{-1}, which was obtained from the smoothed streamflow data on a scale of t_d. The yearly streamflow average from 2001 to 2015 was approximately 12 ± 1 million acre-feet yr^{-1}, with a streamflow deficit $\nu\sigma$ of 3 ± 1.1 million acre-feet yr^{-1}. We find that $\nu_d = 1.5 \pm 0.4$; that is, the Colorado River is currently in a 1.5σ drought.

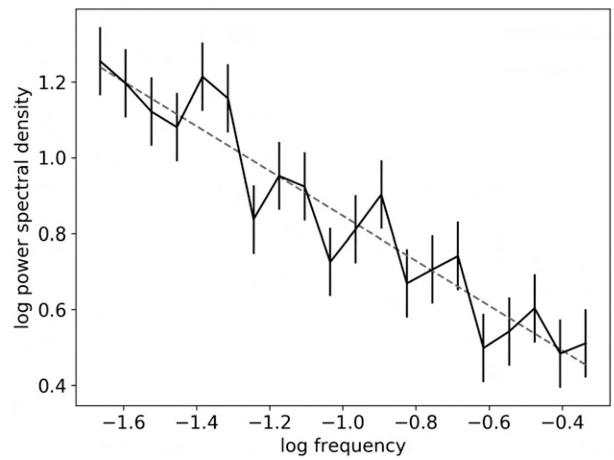


FIG. 3. Power density spectrum of the river flow data measured using the multitaper spectral analysis method (Woodhouse et al. 2006; Mann and Lees 1996). The dashed line shows the best linear fit to the data $\beta = 0.59 \pm 0.07$.

The sixth measured parameter β is the power law index $S(f) \propto f^{-\beta}$, where f is the frequency and $S(f)$ is the power spectrum. This parameter is estimated by performing a least squares regression on log spectral density against log frequency (Pelletier and Turcotte 1997; Huybers and Curry 2006). Values of β near zero describe spectra that have a uniform distribution of variance across frequencies. A positive value of β indicates that the streamflow time series exhibits more variance on longer time scales. This is precisely why an estimate of the mean streamflow based on a time interval of less than several decades is unreliable. Following Woodhouse et al. (2006), we have used the multitaper spectral analysis method (Mann and Lees 1996) to compute the power density spectrum. Figure 3 shows the spectrum plotted on a logarithmic scale versus the log of the frequency. We have fit a power law to this spectrum and derive a value of $\beta = 0.59 \pm 0.07$, consistent with the value quoted by Ault et al. (2013).

Constructing millennia-long tree-ring chronologies from overlapping segments of tree-ring series causes problems for recovering very low-frequency signals (Cook et al. 1995). A few different approaches have been proposed to improve the situation, namely, "signal free" detrending and "regional curve standardization (RCS)" detrending (Briffa and Melvin 2011; Melvin and Briffa 2014).

In summary, the adopted observational values of the parameters used in our model are $\mu = 15 \pm 0.4$ million acre-feet yr^{-1}, $\sigma = 4.5 \pm 1.6$ million acre-feet yr^{-1},

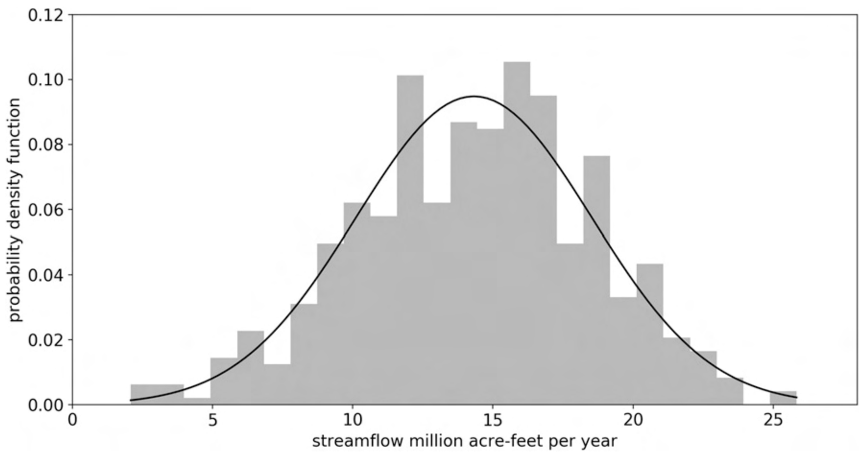


FIG. 4. Normalized histogram of reconstructed Lees Ferry streamflows using Lees-D dataset from Woodhouse et al. (2006). The line shows a Gaussian with same mean and sigma values as the data.

$t_d = 15$ yr, $\sigma_{t_d} = 2 \pm 0.8$, $\nu_d = 1.5 \pm 0.4$, and $\beta = 0.59 \pm 0.07$. These values are used for the calculations in the next section.

4. Methods

The methods discussed below are based on the observation that streamflow data are normally distributed and therefore the result of a Gaussian process (Ault et al. 2013). Figure 4 shows a histogram of the streamflows inferred from the tree-ring analysis of Woodhouse et al. (2006). We used the Lilliefors test (Conover 1980) to test for normality. For the streamflow data analyzed in this paper, the assumption of normality could not be rejected (Lilliefors test; $p < 0.05$). Gaussian fluctuations can be fully characterized by their power spectrum (Strzepek et al. 2010). An array of mathematical tools for analyzing these fluctuations can be applied to the data by assuming the Fourier components of the streamflow time series are independent of each other and with random phases. When working with the streamflow data, it is convenient to define a quantity $\delta(t)$, which is equal to the streamflow measurement $s(t)$ minus the mean streamflow value for the entire dataset $\delta(t) = s(t) - \mu$. It is $\delta(t)$, which we expand as a Fourier series to compute the power spectrum.

Reconstructed streamflows at Lees Ferry show that $S(f) \propto f^{-\beta}$ where $\beta > 0$. This positive β value means low-frequency variations have higher amplitude than high-frequency variations. The statistical properties of the variations can be characterized by the Fourier transform of the power spectrum, the correlation function $\xi(\tau)$. The correlation function can be also directly computed from the data since $\xi(\tau) = \langle \delta(t)\delta(t+\tau) \rangle$.

Mathematically, a drought is defined as a value of $\delta(t)$ less than zero. We characterize the deviation in units of sigma as a $\nu\sigma$ event. The clustering of $\nu\sigma$ events is dependent on the value of these parameters and can be computed from the power spectrum (Rice 1944). The magnitude and length of the droughts depends on correlation of the streamflow. Figure 5 shows simulated streamflows with the same mean and year-to-year scatter as the actual data, but with no correlation from year to year. The simulated 15-yr droughts are less pronounced and less strongly correlated than the real droughts shown in Fig. 1.

To understand why this is, Fig. 6 shows an example illustrating that the presence and clustering of droughts is sensitive to the size of long-term variations in the streamflow. High-amplitude low-frequency fluctuations in the streamflow have the effect of enhancing a drought beyond a critical threshold, and bring about the clustering of droughts shown as shaded areas in the figure. Without these long-term fluctuations, the depth and clustering of droughts would be greatly diminished.

In the Colorado River system, a significant drought is one that will deplete all of its stored water reserves. For reference, the current drought has already depleted about half of the river's reserves. What we would like to know is the probability of the current drought continuing into the near future, essentially putting the remainder of the water reserves at risk. We outline below a method for calculating this probability.

Given that $\delta(t)$ has a Gaussian distribution, the probability of a drought of amplitude $\geq \nu\sigma$ in any given year is represented by

$$P_1 = \int_{-\infty}^{-\nu\sigma} P(y)\, dy, \qquad (1)$$

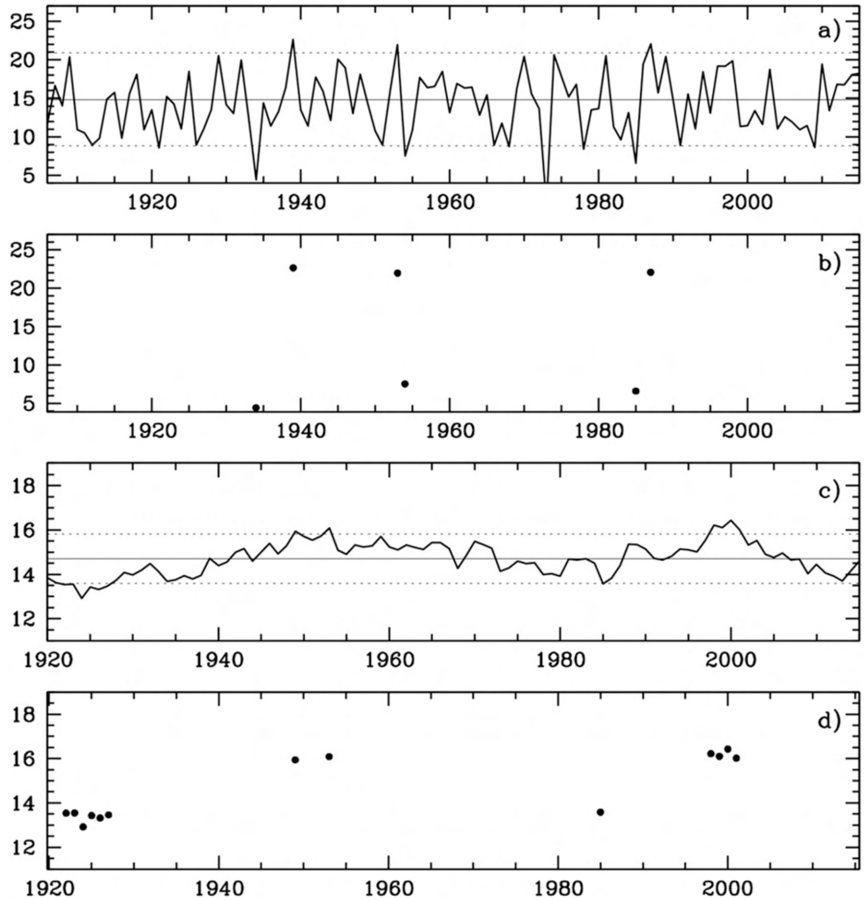


FIG. 5. As in Fig. 1, but for simulated data drawn from a Gaussian generator with mean and RMS deviations identical to the observations. There is no correlation in the simulated data. Note that the RMS deviations in the smoothed simulated data shown in (c) are less than those for the data in Fig. 1 because there is no correlation in the model data. Note also that when there is no correlation, the droughts exceeding the 1.5σ threshold are less pronounced and less strongly correlated than in the actual data shown in Fig. 1.

where

$$P(y) = \frac{1}{\sqrt{2\pi\sigma}} e^{-y^2/2\sigma^2}. \quad (2)$$

The probability that y_1 and y_2 lie below a threshold is given by

$$P_2 = \int_{-\infty}^{-\nu\sigma}\int_{-\infty}^{-\nu\sigma} P(y_1, y_2)\, dy_1 dy_2. \quad (3)$$

We want to know the probability of two such events occurring separated by a given time interval τ. If there is no correlation in the system, the joint probability is just the product of the two probabilities:

$$P(y_1, y_2) = \frac{1}{2\pi\sigma} e^{-y_1^2/2\sigma^2} e^{-y_2^2/2\sigma^2}. \quad (4)$$

If the correlation function is nonzero, it can be shown that the joint probability distribution is

$$P(y_1, y_2) = (2\pi)^{-1}[\xi^2(0) - \xi^2(\tau)]^{-1/2} \times \exp\left\{-\frac{\xi(0)y_1^2 + \xi(0)y_2^2 - 2\xi(\tau)y_1y_2}{2[\xi^2(0) - \xi^2(\tau)]}\right\}. \quad (5)$$

Equation (5) is derived in appendix A. Integrating this equation and dividing by P_1, we obtain the conditional probability of a second drought occurring immediately following another drought. In other words, Eq. (6) is used to calculate the probability of a second drought occurring in the Colorado River τ years after the current drought:

$$P_{2|1} = \frac{P_2}{P_1} = P_1 \times (2/\pi)^{1/2}[\mathrm{erfc}(\nu/2^{1/2})]^{-2} \times \int_{\nu}^{\infty} e^{-y^2/2}\mathrm{erfc}\left(\frac{\nu - y\xi(\tau)\xi(0)}{\{2[1 - \xi^2(\tau)/\xi^2(0)]\}^{1/2}}\right) dy. \quad (6)$$

Several observational parameters are needed to compute $P_{2|1}$ from Eq. (6). Our starting data are the river

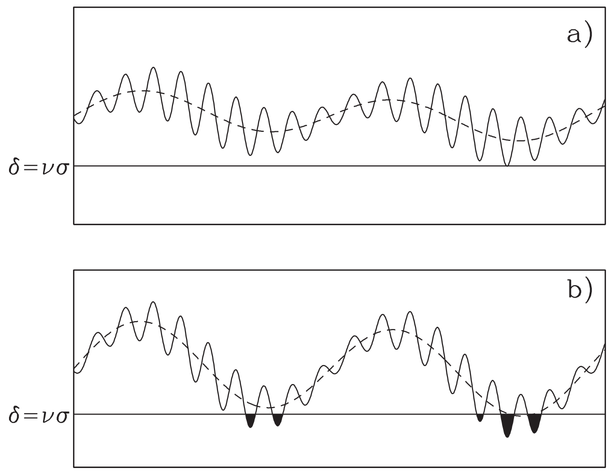


FIG. 6. Illustration of the effect of low-frequency multidecadal streamflow variations on the correlation of droughts. (b) The more pronounced low frequency fluctuations, which have the effect of drawing the streamflow below a drought threshold in a manner that produces several closely spaced droughts where (a) there might have been none at all. Droughts are shown as shaded regions where the streamflow drops below a threshold shown as a horizontal line. The threshold has the value $\nu\sigma$, where σ is the RMS of the streamflow.

streamflow as a function of time $s(t)$. We then compute the mean μ of this river streamflow over the longest period available. We then compute $\delta(t) = s(t) - \mu$. We compute σ, the RMS value of $\delta(t)$. We can then specify the parameter ν corresponding defined by $\delta(t) = \nu\sigma$. Equation (6) then enables one to compute the probability of a value of $\delta(t+\tau) < -\nu\sigma$ occurring at a time τ after an occurrence of $\delta(t) < -\nu\sigma$. The $\xi(\tau)$ is the Fourier transform of the power spectrum, $\xi(0) = \sigma^2$. We derive a value of β from the streamflow data. The power spectrum is then normalized to produce the observed value of σ.

Although it is not explicitly stated in Eq. (6), we can do this analysis not only for the raw streamflow $s(t)$, but also for the streamflow smoothed on a time scale t_d, our drought time scale, because a smoothed Gaussian field is also a Gaussian field. The mean will remain unchanged, but σ will decrease. To compute the correlation function of the smoothed data, one does the smoothing in Fourier space and then computes the Fourier transform of the power spectrum.

The method outlined above allows for the estimation of the length of a drought once it has begun. A variant of this method enables one to compute samples of yearly future streamflows constrained by recent streamflow measurements (Fig. 7). We start with a set of data points δ_i measured at time t_i and a correlation function $\xi(\tau)$. The method allows us to estimate the yearly mean and variance of the river's streamflow for a specified period of time into the future. Using this computed information we make realizations or predictions of actual river streamflows subject to the prior knowledge of past river streamflows. We assume that $\delta(t)$ is a random field with zero mean.

The covariance matrix is defined by $K_{ij} =< \delta(t_i)\delta(t_j) >\equiv \xi(|t_i - t_j|) \equiv \xi(\tau)$. In practice we compute the Cholesky decomposition, also known as the matrix square root $\mathbf{L}$

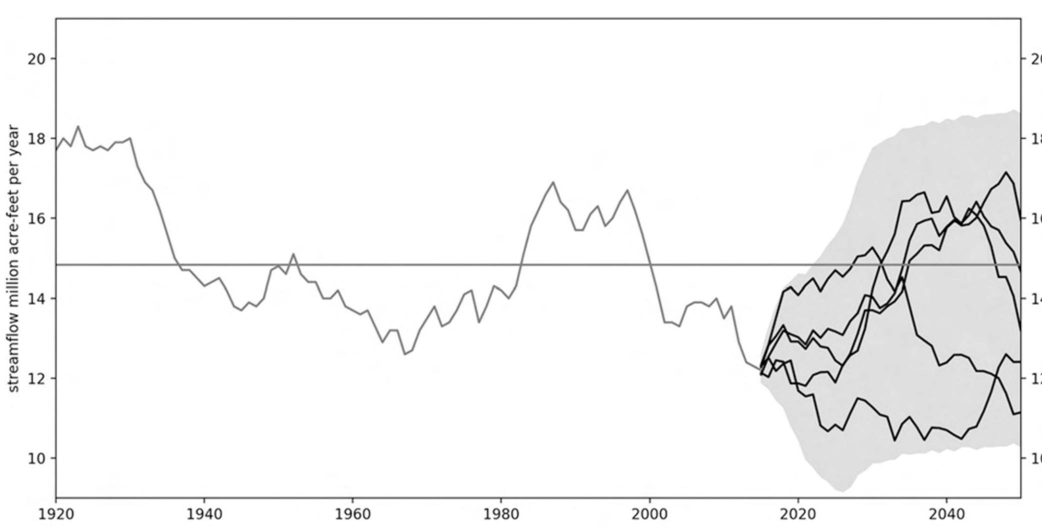


FIG. 7. Predictions for future river streamflows based on the known streamflows for the past 20 years and the correlation properties ($\beta = 0.5$) of the streamflows based on the tree-ring analyses. Measured streamflow is smoothed with a 15-yr boxcar from 1920 to 2015 (gray) After 2015, black lines show five specific predictions of 15-yr average streamflows. The gray shaded area shows $\pm 1.5\sigma$ deviations from the mean.

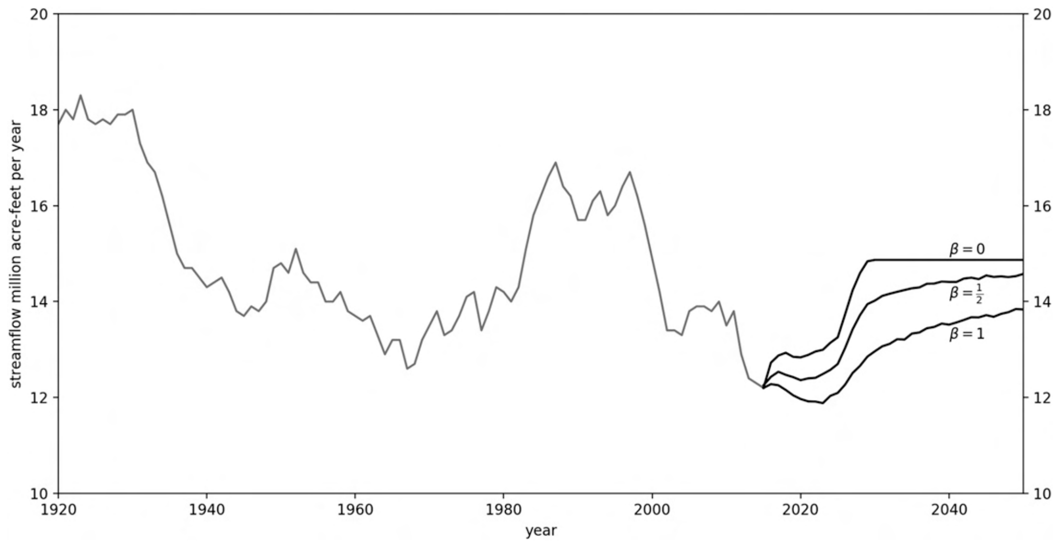


FIG. 8. The β dependence of predictions for future, 15-yr running average of river streamflows based on the known streamflows for the past 20 years and the correlation properties of the streamflows based on the tree-ring analyses. Flows are smoothed with a 15-yr boxcar from 1920 to 2015 (gray line). After 2015, we show three predicted mean streamflows for $\beta = 0$ (upper line; no correlation), $\beta = 0.5$ (middle line), and $\beta = 1$ (lower line).

of the covariance matrix such that $\mathbf{K} = \mathbf{L}\mathbf{L}^{\mathrm{T}}$. We then generate a vector $\mathbf{u}$ that consists of numbers drawn from a Gaussian with zero mean and RMS = 1. Using this vector we can generate a vector $\boldsymbol{\delta} = \mathbf{L}\mathbf{u}$ that has the desired distribution with zero mean and covariance specified in advance (Rasmussen and Williams 2006). This method of Gaussian process regression or constrained random fields has been described by, among others, Rasmussen and Williams (2006), Hoffman and Ribak (1991), and Van de Weygaert and Bertschinger (1996). A description of the implementation of this method is given in appendix B.

5. Results and predictions

Given a known power spectrum of fluctuations, the main result of this paper is a prediction of the probability $P_{2|1}$ of a second drought occurring in a specified time interval following a first drought. In the absence of correlation, $P_{2|1}$ would simply be P_1, the probability of an isolated drought occurring. We begin by computing P_1, the probability of a drought comparable to or deeper than the one currently affecting the Colorado River. We then compute the conditional probability of a second drought occurring τ years after the first drought.

The parameters of the first drought are determined from the direct natural streamflow measurements for the last 15 years. From section 3, we have $t_d = 15\,\mathrm{yr}$, $\sigma_{t_d} =$ 2 million acre-feet yr^{-1}, and $\nu_d = 1.5$; σ_{t_d} is computed from the power spectrum, which is completely specified by the β and σ values. Since a smoothed Gaussian distribution is also Gaussian, the probability of an isolated 15-yr drought (P_1) is a value $\leq -1.5\sigma$ in the smoothed streamflow (i.e., $P_1 = 0.067$).

We compute $P_{2|1}$ using Eq. (6) from section 4. We computed the probability of a second drought occurring following the first drought in a time interval of 7–17 years to be 80%. If the correlation properties remain unchanged within the next decade, there is a high probability of the system remaining in a state of drought for another decade or two.

The parameters have associated errors and can change as our understanding evolves. It is worth looking at the sensitivity of this result to the input parameters. If we increase β, the slope of the power law index, the probability of a second drought increases. This is the parameter that is subject to the greatest uncertainty. Figure 8 shows the dependence of future mean streamflow projections on the parameter β.

The plausible range for β is 0.4–0.7. As we increase the depth of the initial drought ν_d, the probability of a second drought decreases. However, if the current drought is severe enough, it can still completely deplete water reserves for the Colorado River with a magnitude comparable to two consecutive droughts. A 2σ drought over 15 years gives a cumulative deficit of 60 million acre-feet, equal to the entire storage capacity of the Colorado River system. If we increase the time scale of the first drought without changing the other parameters, the probability of a second drought goes up. In other words, it appears that correlation makes things worse for the Colorado River.

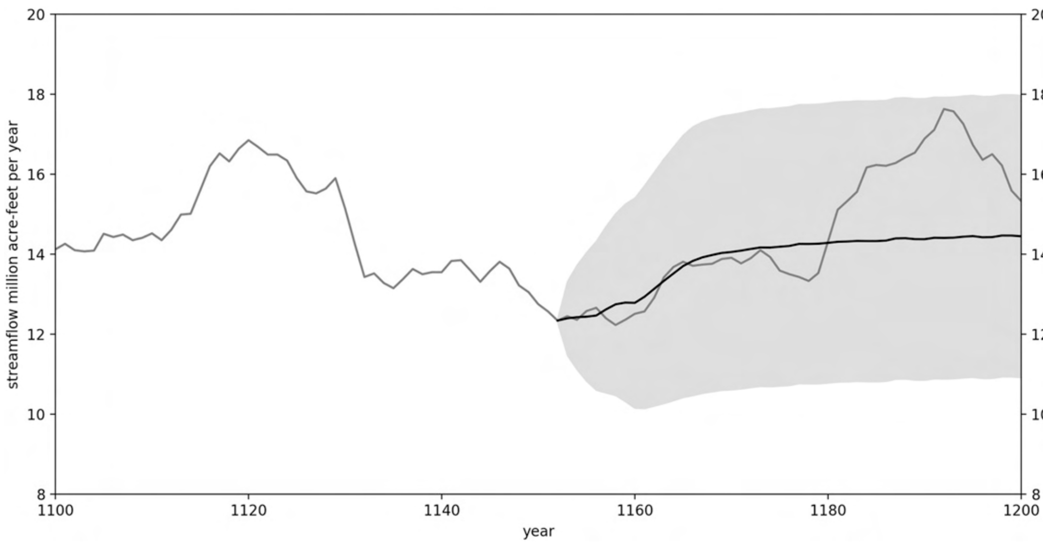


FIG. 9. Testing the model using paleo data. The gray line shows the Colorado River streamflows during the megadrought of the mid-twelfth century. The black line shows the prediction of the mean streamflow, starting from mid-century until the end of that century. The gray area shows the predicted two sigma deviations from the mean prediction.

Correlation can also create danger on the surplus side when streamflows are above average. In 1983, an above-average snowpack put Glen Canyon Dam at risk because of cavitation in the spillways (Moyes and Burgi 1983; Burgi et al. 1984; Burgi and Eckley 1987). The system is vulnerable to extreme events on both sides of the mean (Taleb 2012). It just requires a sign change to compute the probability of streamflows above the mean using the formalism presented in this paper.

We have tested the accuracy of the model for predicting the continuation of persistent droughts using the paleorecord. Figure 9 shows our prediction of the continuation of a megadrought in the twelfth century. The model does reasonably well for 30 years, and then past that does not accurately predict the flows, although the observed flows fall within the predicted range. This confirms that the model can be a useful tool for predicting streamflows on the time scales of decades once the drought has begun.

6. Conclusions

We have presented a method for estimating the length of a drought once it has begun. This is pertinent to the current drought affecting the Colorado River system. As of 2015, the storage in the reservoirs for the Colorado River was approximately 27 million acre-feet (USBR 2015). We estimate the current drought may result in a future deficit of approximately 45 million acre-feet of water.

The Colorado River system's ability to supply its consumers using amounts of water dictated by the Colorado River Compact is in jeopardy for three reasons. First, the long-term yearly mean of streamflows inferred from tree-ring analysis does not match the demand built into the system. Second, the water storage in the system, approximately four years of streamflows, is insufficient to weather the fluctuations in streamflows, which can exceed water storage capabilities on time scales longer than a decade. Last, the issue of modeling precipitation is complex and subtle (Pierrehumbert et al. 2007), which contributes to an inability to reliably predict the detailed and basin-specific consequences of man-made climate change on relevant time scales and spatial scales.

With all this in mind, our method makes use of two datasets, the direct streamflow measurements and tree-ring measurements of the Colorado River system. We used the tree-ring streamflow reconstructions (Meko et al. 2012) to characterize the correlations in the streamflows over the past several centuries. These data were combined with direct streamflow measurements (USBR 2012) to constrain model parameters and predict future streamflows. We conclude with an 80% probability that the current drought will continue long enough into the future to deplete all existing water storages for the Colorado River system.

This prediction, however, should be considered an underestimation, since climate change models predict an increase in droughts throughout the southwest United States (Ault et al. 2014; Prein et al. 2016; Cook et al. 2018;

Udall and Overpeck 2017; McCabe et al. 2017). Precipitation in the American Southwest is expected to decrease in the future because of carbon dioxide emissions. This will result in more frequent droughts, which in turn will be more pronounced and last longer (Solomon et al. 2009; Strzepek et al. 2010). The uncertainties in this forecast are dependent on the uncertainty in the temperature response to a given amount of carbon dioxide, and the uncertainty of how much carbon dioxide will actually be emitted.

To get a better understanding of the impact of climate change on the Colorado River system, Vano et al. (2014) suggests that models are needed to accurately predict the snowfall in the Rocky Mountains. They believe that the headwaters of the Colorado River are close to the nodal line of drying to the south and wetting to the north. While still not certain, there are strong hints that climate change will exacerbate this problem.

We have also presented the results of calculations aimed at making specific realizations for future yearly streamflows in the Colorado River, subject to the statistical and data constraints described above. The method is described in section 4, with the results shown in Figs. 7 and 8. These specific examples illustrate that we can expect the current drought to continue for approximately one or two more decades. If our analysis is correct, consumers of the Colorado River would have to cut water consumption by at least 30% in order to sustain healthy streamflows. Otherwise, the risk to water shortages may increase if water demand is not properly handled.

Our method assumes that fluctuations in the yearly streamflows are Gaussian and described by a known Fourier power spectrum. This allows us to compute the probability of any other future observations in yearly streamflows in the Colorado River. The method can also be applied to other rivers for which the fluctuations are Gaussian and the fluctuation spectrum is known. Whenever there are long-term correlations in fluctuations, the system will be vulnerable to rare events since these events appear to be correlated in time. The method presented here should be viewed as an additional tool for forecasting streamflows by combining tree-ring and direct streamflow measurements. In no way should this method be viewed as a standalone model for determining future streamflows of a water system.

The problem of drought in more general form can also be stated using Bayes theorem:

$$P(H|D) = P(D|H) \times P(H)/P(D).$$

In our case the hypothesis H is that a drought occurs following the first drought, and the data D are the observations of the drought currently affecting the Colorado River. In our case $P(H) = P(D) = 0.067$. We also see from the time symmetry of the problem that $P(H|D) = P(D|H)$. None of this has to be true in the real world. We could consider the correlation of dissimilar droughts $P(H) \neq P(D)$ and also include climate change (β is a function of time), in which case $P(H|D) \neq P(D|H)$. The Bayesian formalism could thus prove to be useful for more complex analyses than the one presented here.

APPENDIX A

Derivation of Eq. (5)

Equation (5) states the probability of finding two streamflow values y_1 and y_2 separated by a given time interval τ. This probability depends on the values of the covariance function evaluated at times $t = 0$ and $t = \tau$, $\xi(0)$, and $\xi(\tau)$. We begin by computing the normalization of the bivariate Gaussian distribution. We then move to the more general case of evaluating the integral for a function of n variables. Finally, we compute the covariance matrix and express the probability distribution in terms of the covariance matrix. The derivation shown below is reproduced from Sivia and Skilling (2006); we include it below for reference.

We assume the relevant bivariate Gaussian distribution to be of the form

$$G(y_1, y_2) = \exp\left[-\frac{1}{2}(Ay_1^2 + Ay_2^2 + 2Cy_1y_2)\right], \tag{A1}$$

where the two constants satisfy the condition $A^2 > C^2$. Integrating $G(y_1, y_2)$ with respect to y_2 yields

$$g(y_1) = \exp\left(-\frac{1}{2}Ay_1^2\right)\int_{-\infty}^{+\infty}\exp\left[-\frac{1}{2}(Ay_2^2 + 2Cy_1y_2)\right]dy_2. \tag{A2}$$

The integral on the right is most easily evaluated by rewriting the exponent

$$Ay_2^2 + 2Cy_1y_2 = A\left(y_2 + \frac{Cy_1}{A}\right)^2 - \frac{C^2}{A}y_1^2; \tag{A3}$$

substituting Eq. (A3) into the equation for $g(y_1)$ [Eq. (A2)], we get

$$g(y_1) = \exp\left[-\frac{1}{2}\left(A - \frac{C^2}{A}\right)y_1^2\right]\int_{-\infty}^{+\infty}\exp\left[-\frac{1}{2}A(y_2 + \phi)^2\right]dy_2, \tag{A4}$$

where $\phi = Cy_1/A$. The y_2 integral is now like the univariate Gaussian integral

$$\int_{-\infty}^{+\infty} \exp\left(-\frac{x^2}{2\sigma^2}\right) dx = \sigma\sqrt{2\pi}. \quad \text{(A5)}$$

The y_2 integral is like the univariate case apart from the unimportant offset ϕ, with $\sigma^2 = 1/B$, its value is equal to $\sqrt{2\pi/B}$; $g(y_1)$ is Gaussian centered at the origin

$$g(y_1) = g(y_2) = \int_{-\infty}^{+\infty} G(y_1, y_2)\, dy_2 = \sqrt{\frac{2\pi}{A}} \exp\left(-\frac{y_1^2}{2\sigma_{y_1}^2}\right), \quad \text{(A6)}$$

where the variance σ_x^2 is given by

$$\sigma_x^2 = \frac{A}{A^2 - C^2}, \quad \text{(A7)}$$

and we finally obtain

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} G(y_1, y_2)\, dy_1 dy_2 = \frac{2\pi}{\sqrt{A^2 - C^2}}. \quad \text{(A8)}$$

It is possible to generalize Eq. (A1) to the more general case as follows:

$$G(\mathbf{y}) = \exp\left(-\frac{1}{2}\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y}\right), \quad \text{(A9)}$$

where $\mathbf{y}^{\mathrm{T}} = (y_1, y_2)$ in our bivariate case. This can be generalized to Gaussian functions of many variables $\mathbf{y}^{\mathrm{T}} = (y_1, y_2, \ldots, y_N)$, and $\mathbf{H}$ is a real symmetric matrix whose eigenvalues λ_j must all be positive. Equation (A1) can be seen as the special case with $N = 2$, where the elements of $\mathbf{H}$ are given by $H_{11} = H_{22} = A$, and $H_{12} = H_{21} = C$.

We denote the integral of $G(\mathbf{x})$:

$$Z = \iint \ldots \int G(y)\, dy_1 dy_2 \ldots dy_N. \quad \text{(A10)}$$

This can be evaluated by making the substitution

$$\mathbf{y} = \mathbf{O}\mathbf{x}, \quad \text{(A11)}$$

where the columns of the $\mathbf{O}$ matrix are the normalized eigenvectors of $\mathbf{H}$; since the latter are orthogonal to each other this means that

$$(\mathbf{O}^{\mathrm{T}}\mathbf{O})_{ij} = \delta_{ij} \quad \text{and} \quad (\mathbf{O}^{\mathrm{T}}\mathbf{H}\mathbf{O})_{ij} = \lambda_j \delta_{ij} \quad \text{and} \quad \text{(A12)}$$

$$\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y} = (\mathbf{O}\mathbf{x})^{\mathrm{T}}\mathbf{H}(\mathbf{O}\mathbf{x}) = \mathbf{x}^{\mathrm{T}}(\mathbf{O}^{\mathrm{T}}\mathbf{H}\mathbf{O})\mathbf{x} = \sum_{j=1}^{N} \lambda_j x_j^2. \quad \text{(A13)}$$

Taking the determinant of the first part of Eq. (A12) gives

$$1 = \det(\mathbf{O}^{\mathrm{T}}\mathbf{O}) = \det(\mathbf{O}^{\mathrm{T}})\det(\mathbf{O}) = [\det(\mathbf{O})]^2. \quad \text{(A14)}$$

The second part of Eq. (A12) gives

$$\lambda_1\lambda_2 \ldots \lambda_n = \det(\mathbf{O}^{\mathrm{T}}\mathbf{H}\mathbf{O}) = \det(\mathbf{O}^{\mathrm{T}})\det(\mathbf{H})\det(\mathbf{O}) = \det(\mathbf{H}). \quad \text{(A15)}$$

Accordingly, Eq. (A10) reduces to the product of one-dimensional integrals

$$Z = \prod_{j=1}^{N} \int \exp\left(-\frac{1}{2}\lambda_j x_j^2\right) dx_j. \quad \text{(A16)}$$

Hence, we find that

$$Z = \frac{(2\pi)^{N/2}}{\sqrt{\lambda_1\lambda_2 \ldots \lambda_N}}. \quad \text{(A17)}$$

Using Eq. (A15), the N-dimensional Gaussian integral of Eq. (A10) becomes

$$Z = \int \exp\left(-\frac{1}{2}\mathbf{x}^{\mathrm{T}}\mathbf{H}\mathbf{x}\right) d^N\mathbf{x} = \frac{(2\pi)^{N/2}}{\sqrt{\det(\mathbf{H})}}. \quad \text{(A18)}$$

This formula can be checked for the $N = 2$ result of Eqs. (A1) and (A9), in which case $\det(\mathbf{H}) = H_{11} - H_{22} - H_{21}H_{12} = A^2 - C^2$. The quantity of interest to us is the covariance matrix $\boldsymbol{\sigma}^2$. It ijth element is formally defined by

$$(\sigma^2)_{ij} = \langle y_i y_j \rangle. \quad \text{(A19)}$$

The expectation value of any function of the parameters $f(\mathbf{y})$ is given by the multiple integral

$$\langle f(\mathbf{y}) \rangle = \frac{1}{Z}\int f(\mathbf{y}) \exp\left(-\frac{1}{2}\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y}\right) d^N\mathbf{y}. \quad \text{(A20)}$$

Equation (A19) then becomes

$$(\sigma^2)_{ij} = \frac{1}{Z}\int y_i y_j \exp\left(-\frac{1}{2}\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y}\right) d^N\mathbf{y}. \quad \text{(A21)}$$

By writing the multivariate Gaussian in the form

$$\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y} = \sum\sum H_{lm} y_l y_m, \quad \text{(A22)}$$

we can see that the right-hand side of Eq. (A20) is related to the partial derivative of the Gaussian integral Z:

$$-2\frac{\partial}{\partial H_{ij}}(\log_e Z) = \frac{1}{Z}\int y_i y_j \exp\left(-\frac{1}{2}\mathbf{y}^{\mathrm{T}}\mathbf{H}\mathbf{y}\right) d^N\mathbf{y}. \quad \text{(A23)}$$

Thus in conjunction with Eqs. (A19) and (A21), we have

$$(\sigma^2)_{ij} = \frac{\partial}{\partial H_{ij}} \{\log_e[\det(\mathbf{H})]\}. \tag{A24}$$

Since the determinant of a matrix is given by the scalar product of any row or column with its cofactors, we can write

$$\frac{\partial}{\partial H_{ij}}[\det(\mathbf{H})] = h_{ij}, \tag{A25}$$

where h_{ij} is equal to $(-1)^{j-i}$ multiplied by the determinant of the $(N-1)$ squared matrix left by striking out the ith row and the jth column of $\mathbf{H}$. Hence Eq. (A24) becomes

$$(\sigma^2)_{ij} = \frac{h_{ij}}{\det(\mathbf{H})}. \tag{A26}$$

A symmetric matrix h_{ij} is also the ijth cofactor of the transpose of $\mathbf{H}$; therefore, we finally obtain the result

$$\boldsymbol{\sigma}^2 = \frac{\mathrm{adj}(\mathbf{H})}{\det(\mathbf{H})} = \mathbf{H}^{-1}, \tag{A27}$$

where the adjoint of $\mathbf{H}$ in the numerator is a matrix consisting of the cofactors of $\mathbf{H}^{\mathrm{T}}$.

For the two-dimensional case, we have used the notation $\xi(0) = \sigma_{11}$ and $\xi(\tau) = \sigma_{12}$, since the observations y_1 and y_2 are separated by a time difference of τ. We can then evaluate the matrix $\mathbf{H}$ and the integral Z in terms of $\boldsymbol{\sigma}^2$. We then have

$$A = H_{11} = H_{22} = \frac{\sigma_{11}}{\sigma_{11}^2 - \sigma_{12}^2} \quad \text{and}$$
$$C = H_{12} = H_{21} = -\frac{\sigma_{12}}{\sigma_{11}^2 - \sigma_{12}^2}. \tag{A28}$$

The integral Z in this case can be written as

$$Z = 2\pi\sqrt{\sigma_{11}^2 - \sigma_{12}^2} = 2\pi\sqrt{\xi(o)^2 - \xi(\tau)^2}. \tag{A29}$$

Putting all this together gives us Eq. (5) in the main text:

$$P(y_1, y_2) = (2\pi)^{-1}[\xi^2(0) - \xi^2(\tau)]^{-1/2} \times \exp\left\{-\frac{\xi(0)y_1^2 + \xi(0)y_2^2 - 2\xi(\tau)y_1y_2}{2[\xi^2(0) - \xi^2(\tau)]}\right\}. \tag{A30}$$

APPENDIX B

Implementation of the Method

We describe the implementation of the method for readers who may be interested in applying it to other datasets. The description is taken from Rasmussen and Williams (2006), to whom we refer the reader for a much more comprehensive discussion of the application of Gaussian processes to the problem of inference.

The problem we address is how to estimate the mean and variance of the streamflow for a given year, based on measurements available for other years. In our case, we are concerned with predicting mean and variance of future streamflows, but one could equally well use the method for past streamflow or to fill in gaps in a historical record.

The inputs that we use are as follows:

$\mathbf{t}$: list of years for which we have measured data
$\mathbf{y}$: measured streamflow measurements for those years
t_*: the year for which we want to predict the streamflow
$\xi(\tau)$: the covariance function
$\mathbf{K}$: the covariance matrix for years with measured data [$K_{ij} = \xi(\tau)$, where $\tau = |t_i - t_j|$]

The algorithm makes use of the Cholesky decomposition; the Cholesky decomposition of a symmetric, positive definite matrix $\mathbf{K}$ decomposes $\mathbf{K}$ into a product of a lower triangular matrix $\mathbf{L}$ and its transpose (Rasmussen and Williams 2006; appendix A.4):

$$\mathbf{L}\mathbf{L}^{\mathrm{T}} = \mathbf{K}. \tag{B1}$$

To solve $\mathbf{K}\boldsymbol{\alpha} = \mathbf{y}$ for $\boldsymbol{\alpha}$, first solve the system $\mathbf{L}\mathbf{x} = \mathbf{y}$ and then the system $\mathbf{L}^{\mathrm{T}}\boldsymbol{\alpha} = \mathbf{x}$. We write the solution as $\boldsymbol{\alpha} = \mathbf{L}^{\mathrm{T}}\backslash(\mathbf{L}\backslash\mathbf{y})$, where the notation $\mathbf{K}\backslash\mathbf{y}$ is the vector $\boldsymbol{\alpha}$ that solves $\mathbf{K}\boldsymbol{\alpha} = \mathbf{y}$.

We are now in a position to begin:

compute $\mathbf{L}$ = cholesky($\mathbf{K}$).
compute $\boldsymbol{\alpha} = \mathbf{L}^{\mathrm{T}}\backslash(\mathbf{L}\backslash\mathbf{y})$.
compute $\bar{f}_* = \mathbf{k}_*^{\mathrm{T}}\boldsymbol{\alpha}$.

This is the predicted mean streamflow for the year x_*; $\mathbf{k}_*$ is the vector of the covariances between the flow at x_*, the year whose flow we wish to predict and the flows in each of the years for which we have measured data:

compute $\mathbf{v} = \mathbf{L}\backslash\mathbf{k}_*$.
compute the variance of $f_* = \xi(0) - \mathbf{v}^{\mathrm{T}}\mathbf{v}$.

Using this method, we predicted the mean and variance for future streamflows. One can use this information to compute individual realizations of future projections. To generate data samples $\mathbf{y} \sim N(\mathbf{m}, \mathbf{K})$ with known mean (computed for each future year from the previous section) and covariance matrix $\mathbf{K}$ using a scalar Gaussian generator, we proceed as follows:

Use the Cholesky decomposition $\mathbf{K} = \mathbf{L}\mathbf{L}^{\mathrm{T}}$ from the previous section.

Generate a vector **u** of Gaussian random numbers with $\mu = 0$ and $\sigma = 1$.

Compute the vector $\mathbf{y} = \mathbf{m} + \mathbf{L}\mathbf{u}$, which has the desired distribution with mean **m** and covariance **K**.

REFERENCES

Ault, T. R., J. E. Cole, J. T. Overpeck, G. T. Pederson, S. S. 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. Climate*, **26**, 5863–5878, https://doi.org/10.1175/JCLI-D-11-00732.1.

——, G. T. Pederson, J. E. Cole, J. T. Overpeck, and D. M. Meko, 2014: Assessing the risk of persistent drought using climate model simulations and paleoclimate data. *J. Climate*, **27**, 7529–7549, https://doi.org/10.1175/JCLI-D-12-00282.1.

Briffa, K. R., and T. M. Melvin, 2011: A closer look at regional curve standardization of tree-ring records: Justification of the need, a warning of some pitfalls, and suggested improvements in its application. *Dendroclimatology*, M. Hughes, T. Swetnam, and H. Diaz, Eds., Developments in Paleoenvironmental Research, Vol. 11, Springer, 113–145.

Bunde, A., J. F. Eichner, J. W. Kantelhardt, and S. Havlin, 2005: Long-term memory: A natural mechanism for the clustering of extreme events and anomalous residual times in climate records. *Phys. Rev. Lett.*, **94**, 048701, https://doi.org/10.1103/PhysRevLett.94.048701.

——, M. I. Bogachev, and S. Lennartz, 2012: Precipitation and river flow: Long-term memory and predictability of extreme events. *Extreme Events and Natural Hazards: The Complexity Perspective*, *Geophys. Monogr.*, Vol. 196, Amer. Geophys. Union, 139–152.

Burgi, P., and M. Eckley, 1987: Repairs at Glen Canyon Dam. *Concr. Int.*, **9**, 24–31.

——, B. Moyes, and T. Gamble, 1984: Operations of Glen Canyon Dam spillways, 1983. *Proc. Conf. Water for Resource Development*, Coeur d'Alene, ID, ASCE, PAP-0714, https://www.usbr.gov/tsc/techreferences/hydraulics_lab/pubs/PAP/PAP-0714.pdf.

Christensen, N., 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.*, **11**, 1417–1434, https://doi.org/10.5194/hess-11-1417-2007.

Conover, W., 1980: *Practical Nonparametric Statistics*. 2nd ed. Wiley Series in Probability and Statistics, Book 94, John Wiley, 493 pp.

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**, e1400082, https://doi.org/10.1126/sciadv.1400082.

——, J. S. Mankin, and K. J. Anchukaitis, 2018: Climate change and drought: From past to future. *Curr. Climate Change Rep.*, **4**, 164–179, https://doi.org/10.1007/s40641-018-0093-2.

Cook, E. R., K. R. Briffa, D. M. Meko, D. A. Graybill, and G. Funkhouser, 1995: The segment length curse in long tree-ring chronology development for palaeoclimatic studies. *Holocene*, **5**, 229–237, https://doi.org/10.1177/095968369500500211.

——, C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle, 2004: Long-term aridity changes in the western United States. *Science*, **306**, 1015–1018, https://doi.org/10.1126/science.1102586.

Gray, S. T., L. J. Graumlich, J. L. Betancourt, and G. T. Pederson, 2004: A tree-ring based reconstruction of the Atlantic multidecadal oscillation since 1567 A.D. *Geophys. Res. Lett.*, **31**, L12205, https://doi.org/10.1029/2004GL019932.

Hidalgo, H. G., and J. A. Dracup, 2003: ENSO and PDO effects on hydroclimatic variations of the upper Colorado River basin. *J. Hydrometeor.*, **4**, 5–23, https://doi.org/10.1175/1525-7541(2003)004<0005:EAPEOH>2.0.CO;2.

Hoffman, Y., and E. Ribak, 1991: Constrained realizations of Gaussian fields—A simple algorithm. *Astrophys. J. Lett.*, **380**, L5–L8, https://doi.org/10.1086/186160.

Huybers, P., and W. Curry, 2006: Links between annual, Milankovitch and continuum temperature variability. *Nature*, **441**, 329–332, https://doi.org/10.1038/nature04745.

Mann, M. E., and J. M. Lees, 1996: Robust estimation of background noise and signal detection in climatic time series. *Climatic Change*, **33**, 409–445, https://doi.org/10.1007/BF00142586.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt, 2004: Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proc. Natl. Acad. Sci. USA*, **101**, 4136–4141, https://doi.org/10.1073/pnas.0306738101.

——, D. M. Wolock, G. T. Pederson, C. A. Woodhouse, and S. McAfee, 2017: Evidence that recent warming is reducing upper Colorado River flows. *Earth Interact.*, **21**, https://doi.org/10.1175/EI-D-17-0007.1.

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, https://doi.org/10.1029/2007gl029988.

——, ——, ——, ——, ——, ——, and ——, 2012: Upper Colorado River flow reconstruction. IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series 2007-052. NOAA/NCDC Paleoclimatology Program, accessed 12 January 2019, ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/northamerica/usa/upper-colorado-flow2007.txt.

Melvin, T. M., and K. R. Briffa, 2014: CRUST: Software for the implementation of Regional Chronology Standardisation: Part 2. Further RCS options and recommendations. *Dendrochronologia*, **32**, 343–356, https://doi.org/10.1016/j.dendro.2014.07.008.

Moyes, B., and P. Burgi, 1983: Glen Canyon Dam chronology of events: 1983 spill—June 2 1983 through July 23, 1983. Bureau of Reclamation Archives Tech. Rep.

National Research Council, 2007: Colorado River basin water management: Evaluating and adjusting to hydroclimatic variability. The National Academies Press Tech. Rep., 222 pp., https://doi.org/10.17226/11857.

Nowak, K., M. Hoerling, B. Rajagopalan, and E. Zagona, 2012: Colorado River basin hydroclimatic variability. *J. Climate*, **25**, 4389–4403, https://doi.org/10.1175/JCLI-D-11-00406.1.

Pelletier, J. D., and D. L. Turcotte, 1997: Long-range persistence in climatological and hydrological time series: Analysis, modeling and application to drought hazard assessment. *J. Hydrol.*, **203**, 198–208, https://doi.org/10.1016/S0022-1694(97)00102-9.

Pierrehumbert, R. T., H. Brogniez, and R. Roca, 2007: On the relative humidity of the earth's atmosphere. *The Global Circulation of the Atmosphere*, T. Schneider and A. H. Sobel, Eds., Princeton University Press, 143–237.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp, 2008: A stochastic nonparametric approach for streamflow generation combining observational and paleoreconstructed data. *Water Resour. Res.*, **44**, W06423, https://doi.org/10.1029/2007WR006684.

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, https://doi.org/10.1002/2015GL066727.

Rasmussen, C., and C. Williams, 2006: *Gaussian Processes for Machine Learning*. MIT Press, 272 pp.

Redmond, K. T., and R. W. Koch, 1991: Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resour. Res.*, **27**, 2381–2399, https://doi.org/10.1029/91WR00690.

Rice, S., 1944: Mathematical analysis of random noise. *Bell Syst. Tech. J.*, **23**, 282–332, https://doi.org/10.1002/j.1538-7305.1944.tb00874.x.

Sivia, D., and J. Skilling, 2006: *Data Analysis, A Bayesian Tutorial*. Oxford University Press, 264 pp.

Smith, A. B., and R. W. Katz, 2013: US billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases. *Nat. Hazards*, **67**, 387–410, https://doi.org/10.1007/s11069-013-0566-5.

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

Strzepek, K., G. Yohe, J. Neumann, and B. Boehlert, 2010: Characterizing changes in drought risk for the United States from climate change. *Environ. Res. Lett.*, **5**, 044012, https://doi.org/10.1088/1748-9326/5/4/044012.

Switanek, M. B., and P. A. Troch, 2011: Decadal prediction of Colorado River streamflow anomalies using ocean-atmosphere teleconnections. *Geophys. Res. Lett.*, **38**, L23404, https://doi.org/10.1029/2011GL049644.

Taleb, N. N., 2012: *Antifragile: Things That Gain from Disorder*. Random House, 544 pp.

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, https://doi.org/10.1002/2016WR019638.

USBR, 2011: Colorado River basin water supply and demand study. Bureau of Reclamation Tech. Rep., 28 pp., https://www.usbr.gov/watersmart/bsp/docs/finalreport/ColoradoRiver/CRBS_Executive_Summary_FINAL.pdf.

——, 2012: Current natural flow data 1906–2008. Bureau of Reclamation, accessed 12 January 2019, https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.

——, 2015: Colorado River basin natural flow and salt data. Bureau of Reclamation, accessed 12 January 2019, https://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html.

Van de Weygaert, R., and E. Bertschinger, 1996: Peak and gravity constraints in Gaussian primordial density fields: An application of the Hoffman–Ribak method. *Mon. Not. Roy. Astron. Soc.*, **281**, 84–118, https://doi.org/10.1093/mnras/281.1.84.

Vano, J. A., and Coauthors, 2014: Understanding uncertainties in future Colorado River streamflow. *Bull. Amer. Meteor. Soc.*, **95**, 59–78, https://doi.org/10.1175/BAMS-D-12-00228.1.

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, https://doi.org/10.1029/2005WR004455.

Xiao, M., B. Udall, and D. P. Lettenmaier, 2018: On the causes of declining Colorado River streamflows. *Water Resour. Res.*, **54**, 6739–6756, https://doi.org/10.1029/2018WR023153.

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

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




Contents

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

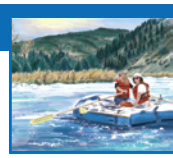
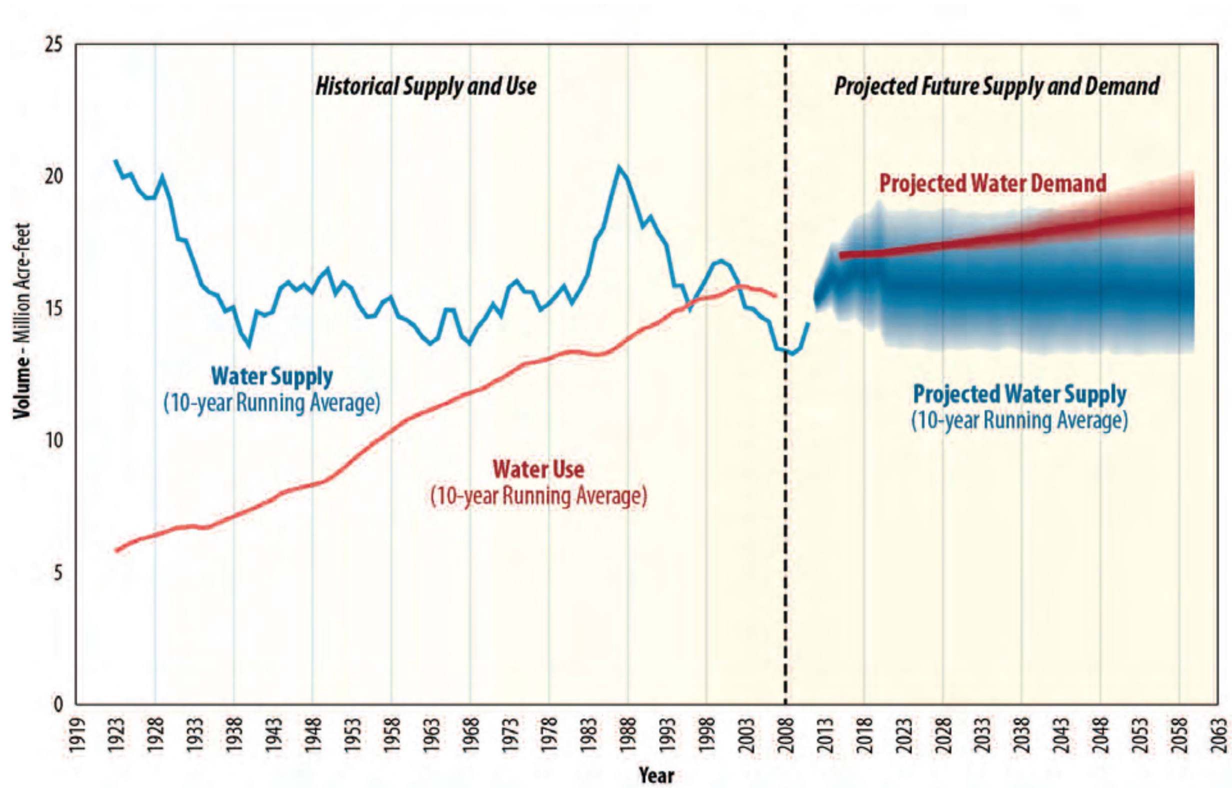



FIGURE 2

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.

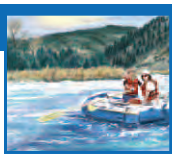


TABLE 1
Criteria Used to Evaluate Representative Options

Technical	Environmental	
Technical Feasibility Implementation Risks Long-Term Viability Operational Flexibility	Permitting Energy Needs Energy Source Other Environmental Factors	
Social	**Other**	
Recreation Policy Legal Socioeconomics	Quantity of Yield Timing Cost	Hydropower Water Quality

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**	

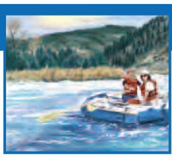


TABLE 2

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.

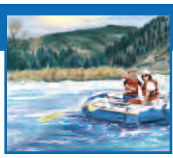
[5] Total does not account for several options that may be mutually exclusive due to regional integration limitations or are dependent on the same supply.

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.

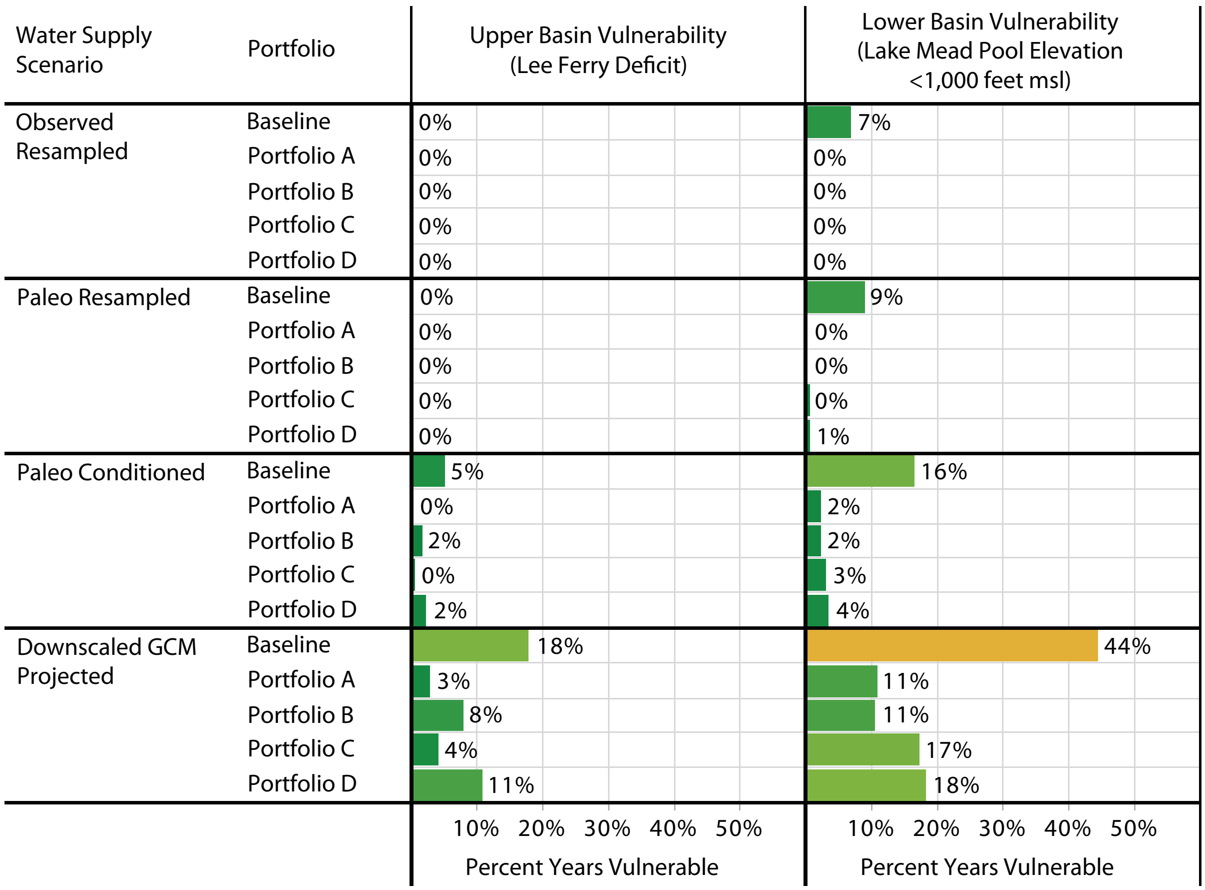
Although the implementation of the portfolios does not completely eliminate the occurrence of such critical vulnerabilities, the portfolios are successful in significantly improving the resiliency of Basin resources to these vulnerable hydrologic conditions. With portfolios in place, the system is able 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

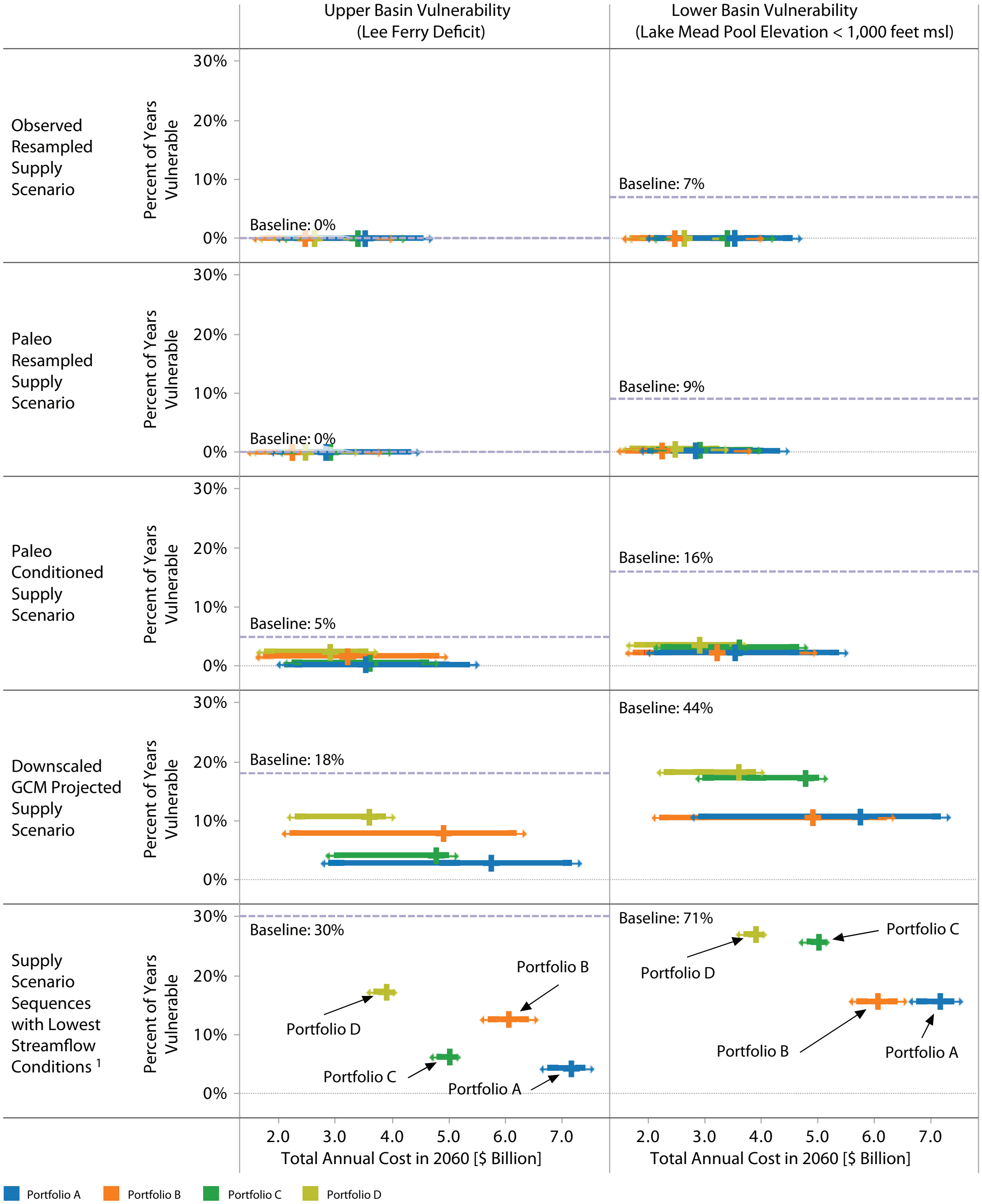


energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. However, this portfolio performs well for addressing the Upper Basin vulnerability (figure 3, left side) and is particularly effective under the Downscaled GCM 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.

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.

RECLAMATION

Managing Water in the West

Colorado River Basin Water Supply and Demand Study

Study Report

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

Study Report

U.S. Department of the Interior
Bureau of Reclamation

December 2012

Acknowledgement

The Colorado River Basin Water Supply and Demand Study represents the most comprehensive analysis ever undertaken within the Colorado River Basin. Its successful completion could only have been accomplished through the dedication and hard work of the Bureau of Reclamation, the consuting team, the seven Colorado River Basin States, and the collaboration of stakeholders throughout the Basin, including federally recognized tribes, agricultural users, purveyors of municipal and industrial water, power users, and conservation and recreational groups. The Study is a model, not only for future basin studies, but for watershed planning across the country, and it will provide the basis for planning for future growth and climate change in the western US and its many watersheds for decades to come.

Special gratitude and appreciation is extended to Christina Robinson-Swett who created the document cover art.

Contents

Figures

Tables

Appendices

Acronyms and Abbreviations

2007 Interim Guidelines	*Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*
2007 Interim Guidelines Final EIS	*Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement*
af	acre- feet
afy	acre-feet per year
Ag	agricultural
Basin	Colorado River Basin
Basin States	Colorado River Basin States
CAP	Central Arizona Project
Compact	Colorado River Compact
CRSS	Colorado River Simulation System
CU&L Reports	Consumptive Uses and Losses Reports
desal	desalination
DOI	U.S. Department of the Interior
GCM	General Circulation Model
ICS	Intentionally Created Surplus
kaf	thousand acre-feet
LB	Lower Basin
M&I	municipal and industrial
maf	million acre-feet
mafy	million acre-feet per year
Mexico	United Mexican States
mod	modification
msl	above mean sea level
Reclamation	Bureau of Reclamation
SECURE	Science and Engineering to Comprehensively Understand and Responsively Enhance
SoCal	Southern California

SSI	self-served industrial
Study	Colorado River Basin Water Supply and Demand Study
tribes	federally recognized tribes
UB	Upper Basin
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity

Study Report

1.0 Introduction

The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States[1] (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). As defined in the *Plan of Study*, the purpose of the Study is 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 does not result in a decision as to how future imbalances will or should 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 may be considered to resolve those imbalances.

Due to the inherent complexities of the Study and the many diverse interests and perspectives of the various stakeholders, interim reports and technical updates were published to reflect continual technical developments and the ongoing input of stakeholders. Throughout the course of the Study, eight of these interim products were published. These documents are listed in *Appendix 2 – Previously Published Documents.* The final documentation for the Study is organized into three major parts: an Executive Summary, this *Study Report* (including appendices), and technical reports (including appendices).

This *Study Report* provides a summary of each of the Study's seven technical reports as well as future considerations and potential next steps that could be conducted as follow-on activities to the Study. This *Study Report* includes seven appendices:

- *Appendix 1 – Plan of Study*
- *Appendix 2 – Previously Published Study Documents*
- *Appendix 3 – Summary of Past Colorado River Basin Planning Studies*
- *Appendix 4 – Study Participants*
- *Appendix 5 – Public Involvement Plan*
- *Appendix 6 – Outreach Activities*
- *Appendix 7 – Peer Review Summary Report*

The seven technical reports summarized in this *Study Report* are listed below:

- ***Technical Report A – Scenario Development.*** This report describes the scenario planning approach used to incorporate uncertainty in future water supply and water demand.

- ***Technical Report B – Water Supply Assessment.*** This report describes the water supply scenarios and presents the analysis and comparison of those scenarios.

---

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

- ***Technical Report C – Water Demand Assessment.*** This report describes the water demand scenarios, presents the analysis and comparison of those scenarios, and presents information on historical consumptive use.
- ***Technical Report D – System Reliability Metrics.*** This report describes the metrics that have been identified for use in the assessment of the reliability of the system to meet resource needs under future supply and demand scenarios.
- ***Technical Report E – Approach to Develop and Evaluate Options and Strategies to Balance Supply and Demand.*** This report provides the overall analytical approach used to analyze opportunities to resolve projected water supply and demand imbalances.
- ***Technical Report F – Development of Options and Strategies.*** This report describes the ideas (options) submitted to the Study to help resolve water supply and demand imbalances and the development of portfolios from those options.
- ***Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies.*** This report presents the reliability of the system to meet resource needs under future water supply and demand scenarios and the effectiveness of options and strategies at improving that reliability.

Project participants and stakeholders are encouraged to comment on the information provided in this *Study Report* and associated technical reports. Written comments should be submitted within 90 days following the release of this report. The comments will be summarized and posted to the Study website, and will be considered in future planning activities in the Basin. Comments may be submitted in the following ways:

1. Via the Study website at http://www.usbr.gov/lc/region/programs/crbstudy.html
2. Email to ColoradoRiverBasinStudy@usbr.gov
3. U.S. mail to U.S. Bureau of Reclamation, Attention: Ms. Pam Adams, LC-2721, P.O. Box 61470, Boulder City, NV 89006-1470
4. Facsimile transmission to 702-293-8418

2.0 Background and Need

Today, almost 40 million[2] people in the seven western states of Arizona, California, Nevada (Lower Division States) and Colorado, New Mexico, Utah and Wyoming (Upper Division States), collectively referenced as the Basin States, rely on the Colorado River and its tributaries to provide some, if not all, of their municipal water needs. That same water source irrigates nearly 5.5 million acres of land[3] in the Basin – producing some 15 percent of the nation's crops and about 13 percent of its livestock, which combined generate many billions of dollars a year in agricultural benefits. The Colorado River is also the lifeblood for at least 22 federally recognized

---

[2] About 40 million people are estimated to be in the Study Area, which encompasses the hydrologic boundaries of the Basin in the United States plus the adjacent areas of the Basin States that receive Colorado River water, by 2015. See *Technical Report C – Water Demand Assessment* for additional detail.

[3] It is estimated that there will be about 5.5 million irrigated acres in the Study Area by 2015. See *Technical Report C – Water Demand Assessment* for additional detail.

tribes (tribes), 7 National Wildlife Refuges, 4 National Recreation Areas, and 11 National Parks. Hydropower facilities along the Colorado River supply more than 4,200 megawatts of vitally important electrical capacity to helping to meet the power needs of the West and reduce the use of fossil fuels. In addition, the Colorado River is vital to the United Mexican States (Mexico). The river supports a thriving agricultural industry in the Mexicali Valley and provides municipal water supplies for communities as far away as Tijuana.

The Colorado River system is operated in accordance with the Law of the River[4]. Apportioned water in the Basin exceeds the approximate 100-year record (1906 through 2011) Basin-wide average long-term historical natural flow[5] 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 and losses in the Basin has averaged approximately 15.3[6] maf over the last 10 years. Figure 1 shows the historical annual Basin water supply (estimated using the natural flow record) and water use[7]. This figure shows that there have been multiple years when use was greater than the supply. 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 during those times. However, there have been periodic shortages throughout the Upper Basin and the adjacent areas of the Basin States that receive Colorado River water.

2.1 Ongoing Efforts to Resolve Water Supply and Demand Imbalances

Throughout the 20th century, the challenges and complexities of ensuring a sustainable water supply and meeting future demand have been recognized. These challenges are documented in several studies conducted by Reclamation and the Basin States over the past six decades (see *Appendix 3 – Summary of Past Colorado River Basin Planning Studies*). Appendix 3 provides a summary of studies which discussed future water supply and demand imbalances and in some cases proposed solutions to dealing with these imbalances.

These studies include:

- *Colorado River Storage Project and Participating Projects; Upper Colorado River Basin* (Reclamation, 1950). This report combined various individual Upper Basin reservoir proposals into a comprehensive plan to increase long-term carryover water storage.
- *Pacific Southwest Water Plan* (Reclamation, 1964). This report projected a Lower Basin water supply and demand imbalance and proposed a comprehensive plan to improve water supply and distribution, including the importation of water from the northern California coastal area.

---

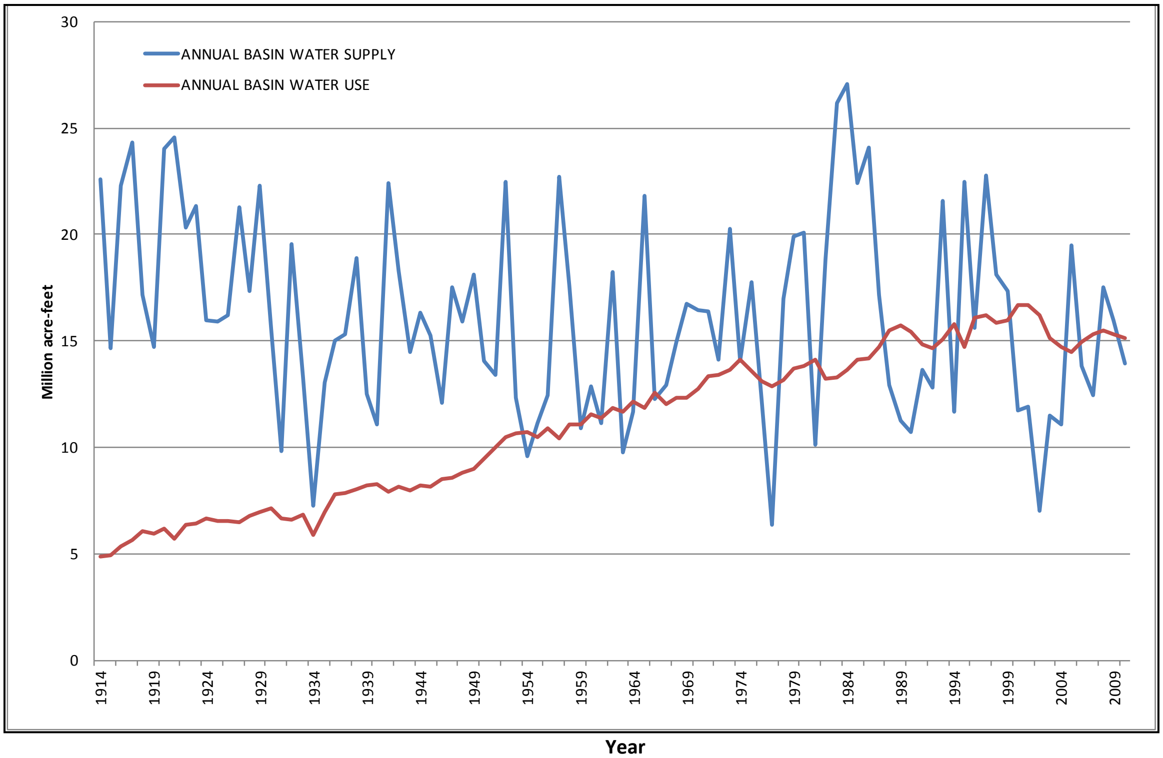
[4] The treaties, compacts, decrees, statutes, regulations, contracts and other legal documents and agreements applicable to the allocation, appropriation, development, exportation and management of the waters of the Colorado River Basin are often collectively referred to as the Law of the River. There 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.

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

[6] 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.

[7] Historical use (as shown in Figure 1) does not necessarily reflect historical water demand, particularly for periods of drought. A decrease in reported use during a drought period may reflect the lack of available supply at the point of use rather than a decrease in the need for water.

FIGURE 1
Historical Annual Colorado River Basin Water Supply and Use



Historical water use is the total use of water throughout the Basin for agricultural, municipal and industrial (M&I), and other consumptive uses including Mexico, plus losses through evaporation at mainstream reservoirs and use by native and non-native vegetation. Natural flow is used as an estimate of water supply in the Basin. In the current natural flow record, historical inflows based on U.S. Geological Survey (USGS gaged records are used as estimates of natural flow for the Paria River, Little Colorado River, Virgin River, and Bill Williams River without adjustment for upstream water uses. However, the Gila River is not included in the natural flow record. Therefore, the use reported here excludes consumptive uses on these tributaries. See Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System for additional detail regarding the treatment of these tributaries in the Study.

- *Comprehensive Framework Study, Lower Colorado Region* (Pacific Southwest Inter-agency Committee, 1971a). This federal-state study projected a Lower Basin water supply and demand imbalance and concluded that a future water import program would be needed as part of a proposed framework program for the development and management of Lower Basin water resources to 2020.

- *Comprehensive Framework Study, Upper Colorado Region* (Pacific Southwest Inter-agency Committee, 1971b). This federal-state study presented a framework program for the development and management of the water and related land resources of the Upper Basin to 2020, including alternative plans with emphases on differing water uses, some of which were dependent on water importation.

- *Westwide Study Report on Critical Water Problems Facing the Eleven Western United States* (Reclamation, 1975). This federal-state study described key factors affecting future water needs, formulated alternative future demand scenarios, and identified options for dealing with anticipated shortages. The study concluded that in spite of conservation, the Basin faces future water shortages unless its natural flows are augmented or water-dependent Basin development is curtailed.

These studies clearly recognized the challenges facing the Basin. The Colorado River Basin Project Act of 1968, which authorized the construction of the Central Arizona Project (CAP), the Southern Nevada Water Project, and other projects in the Lower Basin, further discussed the need for augmentation.[8]

Historically, water planning efforts resulted in the construction of significant infrastructure. Notable examples include Hoover and Glen Canyon Dams, the Central Arizona and Central Utah projects, Colorado's many headwaters trans-basin diversions, California's Colorado River Aqueduct, the All-American Canal, and a wide range of other local and regional water infrastructure projects. In the latter part of the 20th century and in the early portion of the 21st century, focus has shifted from developing available water resources to an emphasis on improving the efficiency of the operation of Colorado River reservoirs and increasing the level of predictability afforded to entities who receive Colorado River water through better planning and managing of available water supplies. Two notable examples from this period are the *Operation of Glen Canyon Dam Final Environmental Impact Statement* (Reclamation, 1996) and the *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead Final Environmental Impact Statement* (2007 Interim Guidelines Final EIS [Reclamation, 2007]). Both of these resulted in the adoption of new reservoir operating policies.

Colorado River stakeholders 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.

2.2 The Need for the Study

Concerns regarding the reliability of the Colorado River system to meet future needs are even more apparent today. The Basin States include some of the fastest-growing urban and industrial areas in the United States. California is ranked among the five fastest-growing states in the country. Arizona and Colorado are in the top 10 fastest-growing states in the country. The continued growth and sustainability of the communities and economies of metropolitan areas such as Albuquerque, Denver, Las Vegas, Los Angeles, Phoenix, Salt Lake City, and San Diego are tied to future water availability from the Colorado River. Water demand for other uses, including the environment, recreation, and tribal water rights settlements, also continues to increase. Potential future increases in temperatures in the Basin, continuing and accelerating a trend observed over most of the Basin during the past 30 to 40 years (National Research Council, 2007), would increase evapotranspiration from vegetation, as well as water loss due to evaporation from reservoirs.

---

[8] Section 202 of the Colorado River Basin Project Act provides in part that "The satisfaction of the requirements of the Mexican Water Treaty, shall be from the waters of the Colorado River pursuant to the treaties, laws, and compacts presently relating thereto, until such time as a feasible plan showing the most economical means of augmenting the water supply available in the Colorado River below Lee Ferry by two and one-half million acre-feet shall be authorized by the Congress and is in operation as provided in this Act."

How climate change and variability affect the Basin water supply has been the focus of many scientific studies. Climate experts expect the southwestern United States to be drier in the future and to experience droughts that are of greater severity than those seen in the past. Recent studies have postulated that the average yield of the Colorado River could be reduced by as much as 20 percent due to climate change (Hoerling et al., 2009). Increasing demands, coupled with decreasing supplies, will certainly exacerbate imbalances throughout the Basin.

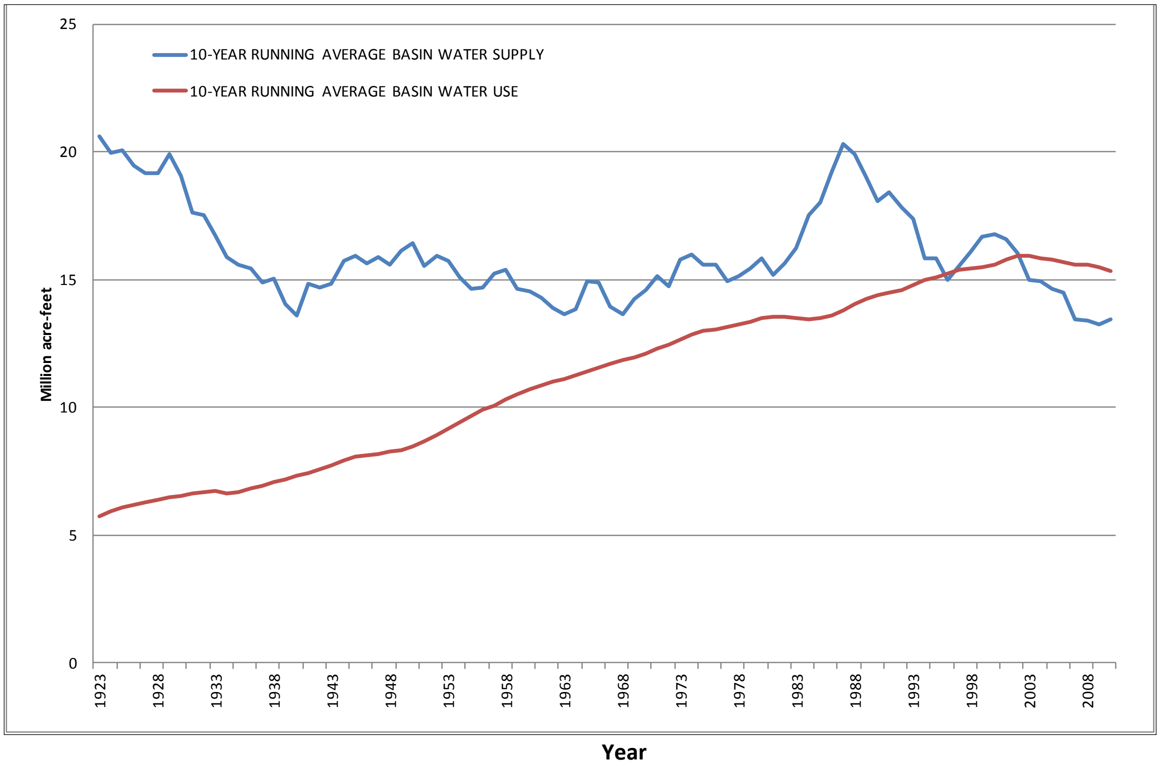
Although a shortage to the Lower Division States (i.e., insufficient water available to satisfy annual consumptive use of 7.5 maf) has not been experienced to date, some water agencies have experienced shortages in water deliveries to their customers in recent years. In California, drought conditions, along with increased regulatory restrictions, caused the Metropolitan Water District of Southern California to reduce firm water deliveries to its customers in 2009 for the first time in nearly 20 years. The water supply allocation plan offered local water providers the flexibility to choose among various conservation strategies, from tiered pricing to limits on outdoor water use, to help ensure that demands stayed in balance with limited supplies. In addition, to help meet critical water supply needs in urban areas, programs have been implemented to fallow land in agricultural areas and transfer the conserved water to urban areas. Although this has helped to meet the water needs of the urban areas, it has also reduced the food and fiber production from the region.

The Upper Basin will need to develop additional water supplies in order to realize full use of its Colorado River Compact apportionment, but such development reduces certainty. Shortages in the Upper Basin are a reality today. Unlike the Lower Basin, which draws its supply from storage in Lake Mead, the Upper Basin is more dependent on annual streamflow to meet its needs.

As of December 10, 2012, Lake Mead is at approximately 51 percent capacity, with a water surface elevation of approximately 1,118 feet above mean sea level (msl). If the current drought continued and water levels in Lake Mead fell to 1,075 feet msl, the amount of water apportioned for use in Arizona and Nevada would be reduced, pursuant to the *Record of Decision for Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead* ([2007 Interim Guidelines] (U.S. Department of the Interior [DOI], 2007). If water levels in Lake Mead fell below 1,025 feet msl, the CAP, which delivers Colorado River water to the Phoenix and Tucson metropolitan areas, would have its supply cut by nearly a third. Under the same circumstance, the Southern Nevada Water Authority's supplies, of which 90 percent come from the Colorado River and serve more than 2 million people in the Las Vegas area, would be curtailed by 20,000 acre-feet (af) annually, nearly 7 percent of Nevada's basic annual apportionment.

Figure 2 presents the data from figure 1 as a 10-year running average to smooth out the annual variability so that trends are more visible. This figure clearly illustrates the existing supply and demand imbalance in the Basin. This imbalance will grow in the future if the potential effects of climate change are realized and demands continue to increase. A combination of options, including conservation and reuse, development of local groundwater supplies, desalination, augmentation, and the transfer of water from agricultural to urban uses, will likely be needed. The Study has assessed these and other options for resolving the projected imbalances in both the Upper and Lower Basins and has laid the foundation from which future discussions can occur to develop recommendations to sustain the environment, people, and economy of this region.

FIGURE 2
Historical 10-Year Running Average Colorado River Basin Water Supply and Use



Historical water use is the total use of water throughout the Basin for agricultural, M&I, and other consumptive uses including Mexico, plus losses due to evaporation at mainstream reservoirs and use by native and non-native vegetation. Natural flow is used as an estimate of water supply in the Basin. In the current natural flow record, historical inflows based on USGS gaged records are used as estimates of natural flow for the Paria River, Little Colorado River, Virgin River, and Bill Williams River. Additionally, the Gila River is not included in the natural flow record. As such, the use reported here excludes consumptive uses on these tributaries. See Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System for additional detail regarding the treatment of these tributaries in the Study.

3.0 Basin Study Program

The Basin Study Program is part of DOI’s WaterSMART (Sustain and Manage America's Resources for Tomorrow) Program[9], which addresses 21st-century water supply challenges such as population growth, increased competition for finite water supplies, and climate change. The establishment of the WaterSMART Program addresses the authorities within the SECURE (Science and Engineering to Comprehensively Understand and Responsively Enhance) Water Act (Subtitle F of the Omnibus Public Land Management Act of 2009, Public Law 111-11), enacted into law on March 30, 2009. The SECURE Water Act provides authority for federal water and science agencies to work with state and local water managers to plan for climate change and other threats to water supplies, and take action to secure water resources for the communities, economies, and the ecosystems they support.

[9] Additional information regarding this program can be found at http://www.usbr.gov/WaterSMART/.

In 2009, Reclamation initiated the Basin Study Program to fund comprehensive studies to define options for meeting future water demands in river basins in the West where imbalances in supply and demand exist or are projected. At that time, it was envisioned that a Basin Study would quantify current and future water supply and demand imbalances, assess the resulting risks to the basin resources, and assess options to resolve those imbalances. Since that time, the Basin Study Program has evolved to focus on the development and analysis of options to address water supply and demand imbalances. The quantification of climate impacts to supply and demand and the subsequent risk assessment are now conducted through an activity known as the West-wide Climate Risk Assessments (another activity under the WaterSMART Program) and are used to inform subsequent Basin studies.

In March 2011, a report to Congress was released to respond to requirements of the SECURE Water Act (Reclamation, 2011a). The SECURE Report provides information on the future risks to water supply in the eight major Reclamation river basins, whereas the Study was a more-detailed, Basin-wide risk assessment that focused on the development and evaluation of opportunities to mitigate and adapt to those risks. There are minor differences in the streamflow projections based on general circulation models presented in the SECURE Report compared to the projections presented in this report. These differences are attributable to methodological and reporting differences between the two efforts and are summarized in a later section of this report and in *Technical Report B – Water Supply Assessment*.

4.0 Study Objectives and Approach

Representatives of the seven Basin States submitted a letter of intent in February 2009, under the Basin Study Program, to help fund and participate in a study of the Basin. Based on that letter of intent, Reclamation's Upper Colorado and Lower Colorado regions, in collaboration with the Basin States, developed and submitted a proposal in June 2009 to fund the Study. The proposal was selected for funding in September 2009, and a financial agreement between the Basin States and Reclamation for the Study was signed in February 2010. Reclamation entered into contracts with CH2M HILL (including Black & Veatch and Cardno-ENTRIX) and the RAND Corporation to provide technical and administrative support for the Study.

The *Plan of Study*, provided in appendix 1, states that the purpose of the Study is 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 *Plan of Study* lays out specific objectives to be addressed through the Study, including:

- Characterization of the current water supply and demand imbalances in the Basin and the assessment of the risks to Basin resources from historical climate variability
- Characterization of future water supply and demand imbalances under varying water supply and demand conditions in the Basin and the assessment of the risks to Basin resources from potential future impacts of climate change

- Identification of potential strategies and options to resolve Basin-wide water supply and demand imbalances, including:
  - Modifications to the operating guidelines or procedures of water supply systems
  - Modifications to existing facilities and development of new facilities
  - Modifications to existing water conservation and management programs and development of new programs
  - Modifications to existing water supply enhancement programs and development of new programs
  - Other structural and non-structural solutions
- Identification of potential legal and regulatory constraints and analysis of potential impacts to water users and Basin resources for the strategies and options considered
- Prioritization of identified strategies and options and recommendations for potential future actions, including feasibility studies, environmental compliance activities, demonstration programs, and/or implementation as appropriate

The Study Area is defined by the hydrologic boundaries of the Basin within the United States, plus the adjacent areas of the Basin States that receive Colorado River water, as depicted in figure 3.

The Study was conducted in four major phases: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for balancing supply and demand. Figure 4 illustrates these phases and some of their inter-relationships.

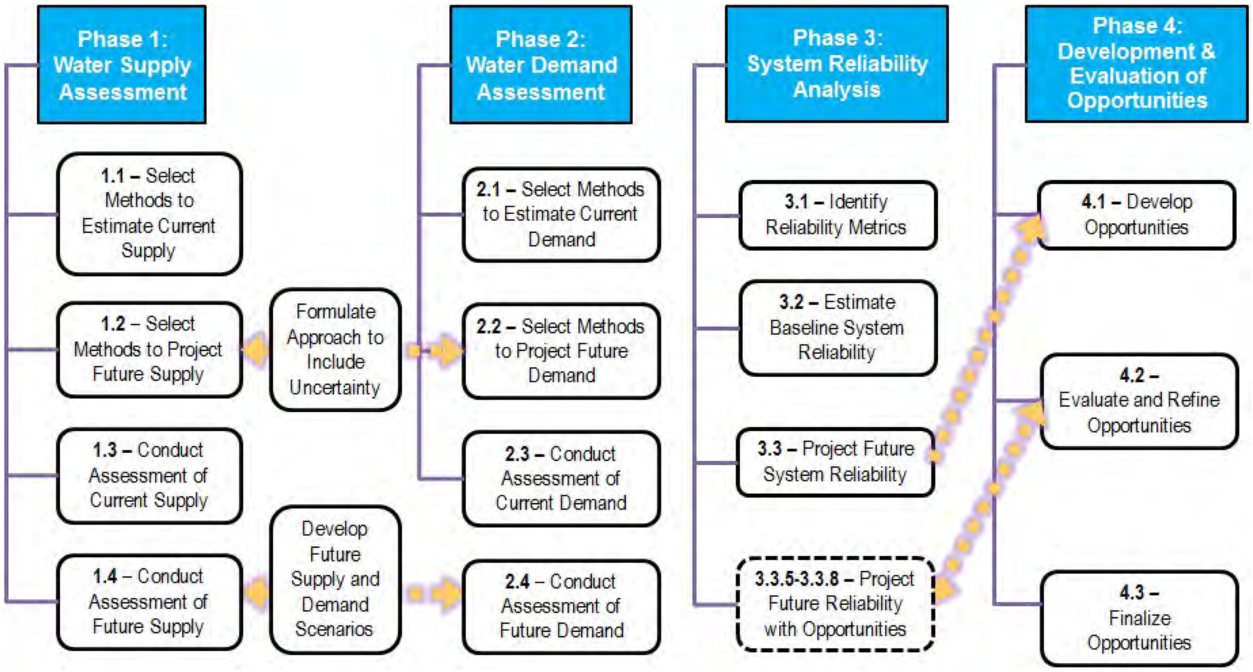
4.1 Study Organization

As envisioned by the *Plan of Study*, two co-Study managers (one from Reclamation and the other representing the Basin States) led and were responsible for the overall direction and management of the Study. In addition, the following teams were established to facilitate the completion of the Study. Members of the Steering, Project, and Study Teams, as well as members of the Study's various technical sub-teams, are listed in *Appendix 4 – Study Participants*:

- The Steering Team (one member from each of Reclamation's Upper Colorado and Lower Colorado regions, one member from each of the seven Basin States, and one member from the Upper Colorado River Commission) steered and guided the efforts of the Project Team such that the objectives of the Study were met in an effective, efficient manner, and within the Study's financial and time constraints. Based on requests from the Ten Tribes Partnership, tribal representatives were invited to participate in Steering Team meetings.
- The Project Team (composed of personnel from the Basin States, water agencies in the Basin States, Reclamation's Upper Colorado and Lower Colorado regions, and from the consulting entities) ensured that the tasks that relate to the Study were completed in a cost-effective, timely manner and were technically sound.

FIGURE 3
The Study Area

FIGURE 4
Study Phases and Tasks



- The Study Team (composed of key personnel from the Upper Colorado and Lower Colorado regions and the consulting entities) completed the Study tasks.
- Sub-teams (composed of Project Team members and representatives from other interested parties with expertise sought by the sub-team) were formed as needed to perform specific technical tasks. Sub-teams consisted of personnel from tribes, conservation organizations, federal agencies, and other interested stakeholder groups.

4.2 Study Outreach

The Study was conducted in collaboration with stakeholders throughout the Basin. Interest was broad and included tribes, agricultural users, purveyors of M&I water, power users, and conservation and recreation groups. Through outreach efforts, interested parties were informed about the Study and asked to provide input reflecting their concerns and thoughts about the future reliability of the Colorado River. This broad participation and input was critical to the Study's success. Interested parties were encouraged to become involved in the Study and were provided a variety of options to do so. These options, which were not mutually exclusive, ranged from attending public meetings and informational webinars to participating directly in the development of work products through the Study's technical sub-teams. The tools and the processes employed in outreach activities are detailed in *Appendix 5 – Public Involvement Plan.* In accordance with the Public Involvement Plan, outreach activities included:

- Establishing a Study website to provide on-line information. The Study web page is http://www.usbr.gov/lc/region/programs/crbstudy.html.
- Establishing an e-mail address to distribute information and receive input. The Study email address is ColoradoRiverBasinStudy@usbr.gov.

- Establishing a facsimile number (702–293–8418) to allow input by fax.
- Establishing a mailing list to ensure that all interested parties receive information, particularly concerning the scheduling and access to public meetings.
- Scheduling public meetings for strategic times during the Study. Six public meetings were conducted during the Study.
- Holding additional meetings with interested parties during the Study period.

More than 170 outreach events occurred during the Study, and these activities are listed in *Appendix 6 – Outreach Activities*.

4.3 Peer Review

A peer review of the Study was conducted to ensure that assumptions, findings, and conclusions of the Study were clearly stated and supported; oversights, omissions, and inconsistencies were identified; and limitations and uncertainties were disclosed. The reviewers were provided with focused technical questions while also being directed to offer a broad evaluation of the overall product.

Peer review comments were considered and incorporated into this and the Study's Technical Reports where relevant and appropriate. *Appendix 7 – Peer Review Summary Report* lists the reviewers, summarizes the comments received and what actions were undertaken to address the reviewers' comments.

In general, the peer review comments indicated that the assessments had been performed adequately and the analyses met the intent of the Study. Many comments dealt with the clarity of the discussion. To address issues of clarity, discussion was added to the reports and description was added to figures and tables as necessary. Study limitations (both in terms of scope and length) prevented the more in-depth supplemental analyses some of the peer reviewers suggestions. Several suggestions for additional analysis are incorporated in the next steps described in section 10.

5.0 Projected Future 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 dependent upon a number of factors. The potential impacts of future climate variability and climate change further contribute to these uncertainties. Nevertheless, projections of future supply and demand were needed to assess the future reliability of the Colorado River system to meet Basin resource needs and to identify options and strategies to mitigate future risks to those resources. These projections had to be sufficiently broad to capture the plausible ranges of uncertainty in future water supply and demand.

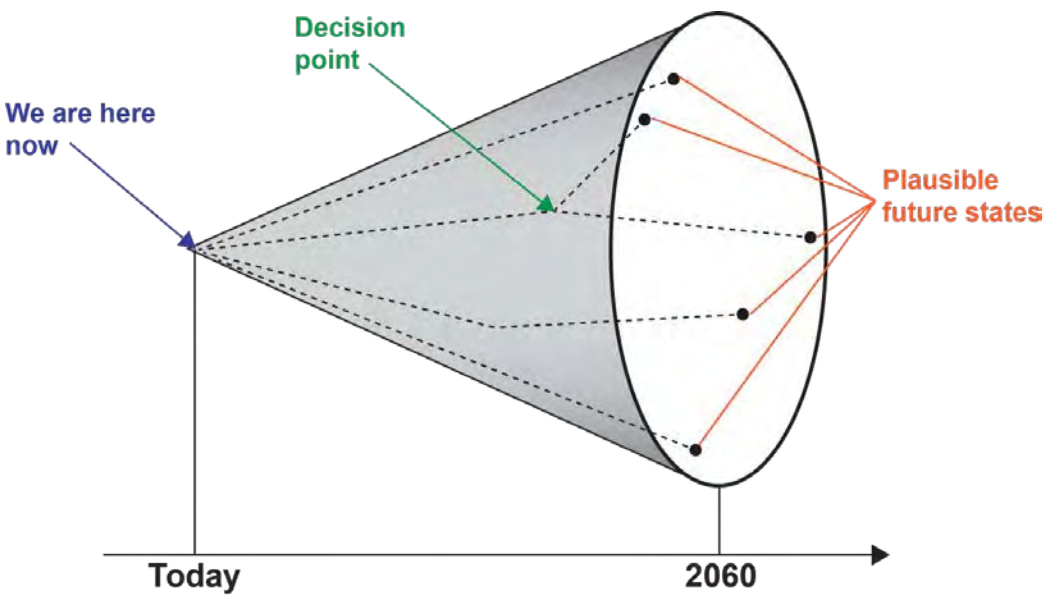
5.1 Summary of *Technical Report A – Scenario Development*

A scenario planning process was used to guide the development of scenarios for providing a broad range of projections of future water supply and demand, resulting in four scenarios related to future water supply and six scenarios related to future water demand. The following section summarizes the approach to scenario development. applied to the Study.

5.1.1 Objective and Approach

Scenarios are not predictions or forecasts of the future. Rather, they are alternative views of how the future might unfold. Figure 5 illustrates this concept. At present, an understanding of the state of the Colorado River system exists as indicated by the single point labeled "Today" on the x-axis of the figure. A range of plausible futures, represented by the funnel, can be identified. The suite of scenarios used in the planning effort should be sufficiently broad to span this plausible range of the funnel.

FIGURE 5
Conceptual Representation of the Uncertain Future of a System, Also Known as "The Scenario Funnel"
Adapted from Timpe and Scheepers, 2003.



The scenario planning process involved:

- Identifying the key forces that would likely drive future water supply and water demand
- Ranking the driving forces (the factors that would likely have the greatest influence on the future state of the system and thereby the performance of the system over time) by their relative importance and uncertainty
- Using the most highly uncertain and highly important driving forces ("critical uncertainties") to identify various themes and "storylines" (narrative descriptions of scenarios) to describe how water supply and water demand may evolve in the future

Quantification of the storylines resulted in water supply and water demand scenarios used to assess future system reliability and thus inform the development of options and strategies to resolve imbalances between water supply and demands.

The general steps involved in the scenario planning process as applied to a water resource planning study were customized to meet the needs of the Study as described in *Technical Report A – Scenario Development.* The approach included input from a broad sampling of stakeholders, experts, and others interested in the management of the system. This input was crucial throughout the development of scenarios to ensure that the resulting scenarios represent the plausible range of futures in the view of those who best know the system.

5.1.2 Summary of Results

A list of 18 specific driving forces relevant to understanding potential future conditions was developed with stakeholder involvement using the general categories listed below and based on experience managing the Colorado River system.

- Natural Systems
- Demographic
- Economic
- Technological
- Social
- Governance

Table 1 lists the driving forces and numbers that were assigned to them. The numbers were assigned for identification purposes only and do not imply a relative priority.

TABLE 1
List of Driving Forces Influencing Future Colorado River System Reliability

No.	Driving Force
1	Changes in streamflow variability and trends
2	Changes in climate variability and trends (e.g., temperature, precipitation)
3	Changes in watershed conditions (e.g., diseases, species transitions)
4	Changes in population and distribution
5	Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes)
6	Changes in urban land use (e.g., conversion, density, urbanization)
7	Changes in public land use (e.g., forest practices, grazing, wilderness areas)
8	Changes in agricultural water use efficiency
9	Changes in M&I water use efficiency
10	Changes in institutional and regulatory conditions (e.g., laws, regulations)
11	Changes to organization or management structures (e.g., state, federal, bi-national institutions)
12	Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear)
13	Changes in flow-dependent ecosystem needs for Endangered Species Act-listed species
14	Changes in other flow-dependent ecosystem needs
15	Changes in social values affecting water use
16	Changes in cost of energy affecting water availability and use
17	Changes in water availability due to tribal water use and settlement of tribal water rights claims
18	Changes in water quality, including physical, biological, and chemical processes

Based on these driving forces, 12 critical uncertainties were identified. Two critical uncertainties primarily affect the future of water supply and 10 critical uncertainties affect the future of water demand.

The two critical uncertainties primarily affecting the future of water supply are (1) Changes in Streamflow Variability and Trends and (2) Changes in Climate Variability and Trends. A set of four scenarios focused around these critical uncertainties was constructed to represent a broad range of plausible future water supply conditionsin the Basin through the next 50 years. The scenarios were informed by the past, present, and projections of possible futures through incorporation of the paleo-reconstructed streamflow record, the observed historical streamflow record, and projections of streamflow using climate projections from general circulation models (GCMs). The four water supply scenarios and associated themes are presented below.

The scenario development approach identified 10 critical uncertainties primarily affecting the future of water demand. These critical uncertainties are displayed in table 2.

TABLE 2
Critical Uncertainties Affecting Water Demand Scenarios

Critical Uncertainty Identified in Survey	General Driving Force Category
Changes in Population and Distribution Changes in Agricultural Land Use (e.g., irrigated agricultural areas, crop mixes)	Demographics and Land Use
Changes in Agricultural Water Use Efficiency Changes in M&I Water Use Efficiency Changes in Water Needs for Energy Generation (e.g., solar, oil shale, thermal, nuclear)	Technology and Economics
Changes in Institutional and Regulatory Conditions (e.g., laws, regulations) Changes in Flow-dependent Ecosystem Needs for Endangered Species Act-listed Species Changes in Other Flow-dependent Ecosystem Needs Changes in Social Values Affecting Water Use Changes in Water Availability due to Tribal Water Use and Settlement of Tribal Water Rights Claims	Social and Governance

After aligning the associations of the critical uncertainties with the key factors of either water supply and demand, the scenario development process was completed based on the process previously described. These critical uncertainties were combined to generate four water supply scenarios and four water demand storylines. These storylines and their associated themes are described below.

Each of the water supply scenarios was quantified and analyzed. That work, including the approach and key results, is documented in *Technical Report B – Water Supply Assessment* and summarized in the next section of this report. The methodology used to quantify the demand scenarios, as well as an assessment of historical consumptive uses and losses, are described in *Technical Report C – Water Demand Assessment* and summarized in subsequent sections of this report.

5.2 Summary of *Technical Report B – Water Supply Assessment*

Four water supply scenarios were developed using the scenario planning approach previously described. This section summarizes the quantification of those scenarios and the resulting range of potential future streamflow in the Basin.

5.2.1 Objective and Approach

The objective of the Water Supply Assessment was to characterize and quantify the probable magnitude and variability of historical and future natural flows in the Basin. Natural flow represents the flow that would have occurred at a location had depletions and reservoir regulation not been present upstream of that location. The assessment included the potential effects of future climate variability and climate change and provides quantified projections of future hydrology.

Using the scenario planning process described above and in *Technical Report A – Scenario Development*, four water supply scenarios were identified and quantified, each representing plausible future water supply conditions. These water supply scenarios and their associated themes are presented in detail in *Technical Report B – Water Supply Assessment.* The following scenarios and associated themes were considered in the Study:

- **Observed Resampled:** Future hydrologic trends and variability are similar to the past approximately 100 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 future downscaled GCM projections.

Before 2004, Reclamation used the historical record of natural flow in planning studies. The implicit assumption was observed natural flow would be representative of future streamflow variability and trends. In 2004, Reclamation initiated a multi-faceted research and development program to develop methods beyond those using the observed record for projecting possible future inflow sequences for Basin planning studies. Through this effort, two additional water supply scenarios were developed; they have been used in previous Basin planning studies that assume the observed and paleo-reconstructed streamflow records are representative of future streamflow variability and trends. These scenarios were most recently detailed in appendix N of the 2007 Interim Guidelines Final EIS. The three scenarios previously used are the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios.

A resampling technique known as the Indexed Sequential Method (Ouarda et al., 1997) was applied to the observed and paleo-streamflow records to generate multiple sequences of future streamflow in the Observed Resampled (102 sequences) and Paleo Resampled (1,244 sequences) scenarios. Sequences for the Paleo Conditioned scenario were generated by applying a non-parametric technique to "blend" the observed and paleo streamflow records (1,000 sequences).

To ensure that the water supply scenarios encompassed a sufficiently broad range of future water supply conditions, a fourth scenario was developed that used downscaled GCM projections, titled the Downscaled GCM Projected scenario.

The Downscaled GCM Projected scenario entailed a method in which climate forcings (primarily temperature and precipitation) from 112 climate projections used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (Intergovernmental Panel on Climate Change, 2007), subsequently bias corrected and statistically downscaled (Maurer et al., 2007), were input to the Variable Infiltration Capacity (VIC) hydrologic model (Christensen and Lettenmaier, 2009) to simulate streamflow. The VIC model (Liang et al., 1994, 1996; Nijssen et al., 1997) is a spatially distributed macro-scale hydrologic model that solves the water balance at each model grid cell. The VIC model was populated with the historical temperature and precipitation data to simulate historical hydrologic parameters (Maurer et al., 2002). *Technical Report B – Water Supply Assessment*, *Appendix B4 – Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations* provides details on the VIC model and its application in the Study. A streamflow bias correction method was developed and applied to the "raw" VIC-simulated flows to account for any systematic bias in the hydrology model and/or climate data sets. The Downscaled GCM Projected scenario consisted of 112 sequences of future streamflow. The 112 climate projections comprised projections assuming three independent greenhouse gas emission scenarios (high, medium, and low), 16 distinct GCMs, and multiple simulations due to differences in starting climate system state (initial oceanic and atmospheric conditions).

These four methods were used to develop hydrologic inputs into the Colorado River Simulation System (CRSS)[10]. CRSS is Reclamation's primary Basin-wide simulation model used for long-term planning studies and, in its current configuration, requires natural flow inputs at 29 locations on a monthly time step over the Study's planning horizon.

5.2.2 Summary of Results

Historical Supply

The Study assessed historical water supply in the Basin. The assessment was composed of a discussion of methods followed by the results for four groups of water supply indicators: climate, hydrologic processes, climate teleconnections, and streamflow. Two historical streamflow data sets, the observed record spanning the period 1906 through 2007 and the paleo-reconstructed record spanning the period 762 through 2005 (Meko et al., 2007), were used to characterize historical streamflow patterns and variability. The following observations and conclusions were made:

- There has been a warming trend in both the Upper and Lower Basins since the 1970s, which is consistent with observed North American and global trends.

[10] CRSS was the primary modeling tool used in the Study. It simulates the operation of the major Colorado River system reservoirs on a monthly time step and provides information regarding the projected state of the system in terms of output variables. Outputs include the amount of water in storage, reservoir elevations, releases from the dams, hydropower generation, the amount of water flowing at various points in the system, the total dissolved solids content, and diversions to and return flows from the water users in the system.

- Widespread decreases in springtime snowpack were observed, with consistent results across the lower elevation northern latitudes of the western United States. Losses of snow water equivalent tended to be largest at low elevations and strongly suggested a temperature-related effect.
- Natural inter-annual variability in streamflow tended to be more dominant than the relationships to either the El Niño–Southern Oscillation or the Pacific Decadal Oscillation. However, in 2011 and 2012, the climate was entering a strong combined cool phase of both El Niño–Southern Oscillation Pacific Decadal Oscillation. The alignment of both signals in the cool phase suggests a propensity for continued drying trends in the coming years.
- The recent deficit (defined as the difference between the 2-year running average flow and the long-term mean annual flow) that started in 2000 is more severe than any other deficit in the observed period, at 9 years and 28 maf.
- The period from 762 through 2005 contained deficits that were longer in duration (16 years) and larger (as much as 35 maf) than those in the period from 1906 through 2005. Thus, the wet–dry sequences from the much longer paleo record suggest that deficits of greater severity than the recent deficit are possible.

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

Future Projected Supply

The Observed Resampled, Paleo Resampled, and Paleo Conditioned methods did not consider the impacts of a changing climate beyond what has occurred historically. Therefore, the key findings related to projected changes in temperature, precipitation, snowpack, and runoff over the next 50 years that may be expected under the Downscaled GCM Projected scenario in particular are presented below. These findings are based on the assessment described in *Technical Report B – Water Supply Assessment.*

- Warming is projected to increase across the Basin, with the largest changes in spring and summer and with larger changes in the Upper Basin than in the Lower Basin. Annual Basin-wide average temperature increases are projected to be approximately 1.3 and 2.4 degrees Celsius over the periods 2011 through 2040 and 2041 through 2070, respectively. Increases are measured relative to the 30-year historical period of 1971 through 2000.
- Precipitation patterns continue to be spatially and temporally complex, but projected seasonal trends toward drying are significant in certain regions. A general trend towards drying is present in the Basin, although increases in precipitation are projected for some higher elevation and hydrologically productive regions. Consistent and expansive drying conditions are projected for the spring throughout the Basin. For much of the Basin, drying conditions are also projected in the summer, although some areas of the Lower Basin are projected to experience slight increases in precipitation, which may be attributed to the monsoonal

influence in this region. Upper Basin precipitation is projected to increase in the fall and winter and the Lower Basin is projected to experience decreases.

- Snowpack is projected to decrease as more precipitation falls as rain rather than snow and warmer temperatures cause an earlier melt. Decreased snowpack in the fall and early winter is projected in areas where precipitation does not change or increases, and is caused by more rain and less snow due to warming. Substantial decreases in spring snowpack are projected to be widespread, due to earlier melt or sublimation of snowpack.
- Runoff (both direct and baseflow) is spatially diverse, but is generally projected to decrease, except in the northern Rockies. As with precipitation, runoff is projected to increase significantly in the higher elevation Upper Basin during winter, but is projected to decrease during spring and summer.

Future Colorado River flows were developed for all water supply scenarios. Figure 6 shows the range of annual flows for the Colorado River at Lees Ferry for each of the scenarios over the Study period.

The long term (2011–2060) mean natural flow for the Colorado River at Lees Ferry over the next 50 years ranged from 14.7 to 15.0 maf for the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios. The Downscaled GCM Projected scenario resulted in mean annual flows of approximately 13.7 maf, an 8.7 percent reduction from the observed mean. The range of mean flows was greatest under the Downscaled GCM Projected scenario, with the inter-quartile range spanning roughly 12.6 to 14.9 maf and the minimum/maximum range covering 10 to 17 maf.

A skew of zero implies a normal distribution, in which wetter years and magnitudes are evenly balanced with drier years. Most scenarios had a positive skew, suggesting a bias to the drier side of the distribution. This was particularly noticeable in the Downscaled GCM Projected scenario.

The minimum annual flows were fairly consistent across the scenarios, with the Paleo Resampled scenario exhibiting the most extreme low-flow condition. The Downscaled GCM Projected scenario exhibited a range of maximum annual flows not seen in any of the other scenarios.

Table 3 presents a comparison of several key streamflow statistics for each scenario. The statistics are grouped by annual, monthly, deficit, and surplus period statistics. For the purpose of the Study, deficit and surplus periods occur whenever the running 2-year average flow falls below (deficit) or above (surplus) 15.0 maf, the observed mean. Deficit and surplus period statistics indicate the range of inter-annual variability of streamflow across the scenarios.

In comparison to the Observed Resampled scenario, the other scenarios exhibited a substantial increase in inter-annual variability, both in sustained deficits and surpluses. The maximum length of sustained deficit in the Observed Resampled scenario was 8 years, whereas the maximum sustained surplus was 7 years. The Paleo Resampled, Paleo Conditioned, and Downscaled GCM Projected scenarios all produced deficit and surplus periods that were much longer. The frequency of deficit spells that were 5 years or longer was also higher under these scenarios, with the Downscaled GCM Projected scenarios exhibiting a likelihood of almost 50 percent over the next 50 years. However, the frequency of surplus spells that were 5 years or longer was highest under the Observed Resampled scenario.

FIGURE 6
Summary Statistics for Annual Colorado River at Lees Ferry Natural Flows for Supply Scenarios
Figure shows the median (dash), 25th–75th percentile band (box), and maximum/minimum (line).

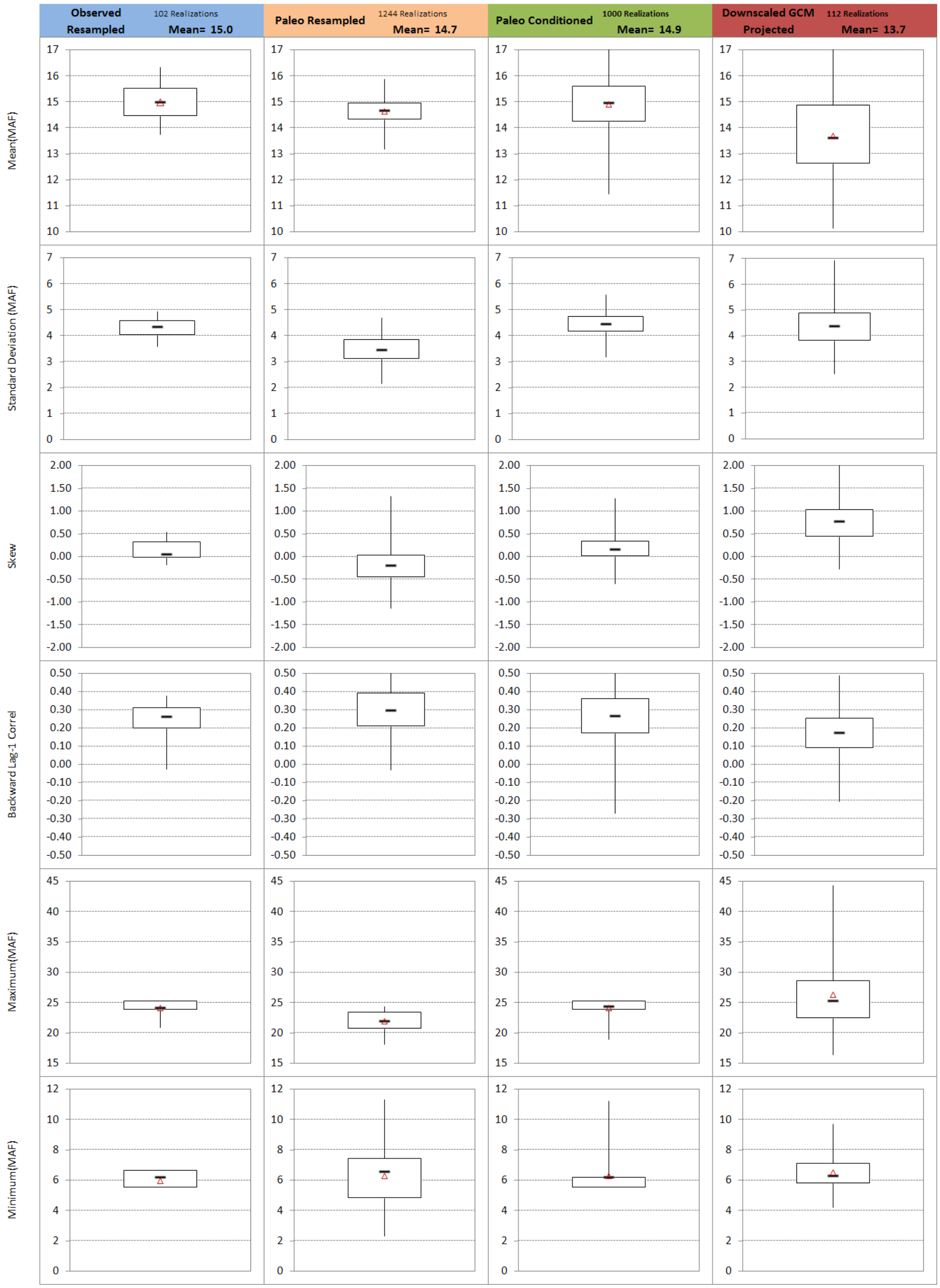


TABLE 3
Summary of Key Streamflow Statistics for Each Water Supply Scenario

	Statistic[1]	Scenario			
		Observed Resampled	**Paleo Resampled**	**Paleo Conditioned**	**Downscaled GCM Projected**
Annual (Water Year)	Average Annual Flow (maf)	15.0	14.7	14.9	13.7
	Percent Change from Long-term Mean (1906–2007)	0%	-2%	-1%	-8.7%
	Median (maf)	15.0	14.7	15.0	13.6
	25th Percentile (maf)	14.5	14.3	14.2	12.6
	75th Percentile (maf)	15.5	15.0	15.6	14.9
	Minimum Year Flow (maf)	5.6	2.3	5.6	4.2
	Maximum Year Flow (maf)	25.2	24.3	25.2	44.3
Monthly	Peak Month	June	June	June	June
	Peak Month Mean Flow (thousand acre-feet [kaf])	4,007	3,914	4,000	3,393
	Peak Month Maximum Flow (kaf)	8,467	8,531	8,678	14,693
	Month at Which Half of Annual Flow (Water Year) was Exceeded	June	June	June	June
Deficit Periods[2]	Maximum Deficit (maf)	28.2	38.4	98.5	246.1
	Maximum Spell Length (years)	8	17	24	50
	Intensity (Deficit/Length) (mafy)	3.5	2.3	4.1	7.4
	Frequency of 5+ Year Spell Length (percent)	22%	30%	25%	48%
	Maximum 8-year Deficit (longest in 1906–2007 observed record, maf)	28.2	29.8	50	48.6
Surplus Periods[3]	Maximum Surplus (maf)	22.2	36.2	88	74.7
	Maximum Spell Length (years)	7	15	25	19
	Intensity (Surplus/Length) (mafy)	3.2	2.4	3.5	13.2
	Frequency of 5+ Year Spell Length (percent)	28%	15%	18%	<1%
	Maximum 7-year Surplus (longest in 1906–2007 observed record, maf)	22.2	29.2	44	39.2

[1] Statistics are computed over the Study period, 2011–2060.
[2] A deficit period occurs whenever the running 2-year average flow is below the observed mean from 1906–2007 of 15.0 maf.
[3] A surplus period occurs whenever the running 2-year average flow is above the observed mean from 1906–2007 of 15.0 maf.

The results suggest that under sequences in the Downscaled GCM Projected scenario, sustained periods of dryness may occur (deficit lengths of up to 50 years). Most projections resulted in long-term mean annual flows that were less than the 15 maf observed mean, while other projections resulted in long-term mean annual flows that were greater than the 15 maf observed mean. The future projected climate essentially arrived at a new mean state.

The processes in which GCM projections were used to generate projections of future streamflow contained a number of areas of uncertainty and reflected methodological choices made in the Study. For example, different methodological choices with respect to downscaling techniques, as well as selection of a different hydrologic model used to translate GCM output into streamflow, yielded different results.

There are some minor methodological differences in the technical approach to develop streamflow projections informed by GCMs and the analysis of those projections between the results presented here and those presented in the SECURE Report. The methodological differences consist primarily of the application of a secondary bias correction to the results presented here. Reporting differences are due to the selection of baseline conditions for comparison and the future analysis period. Specifically, the SECURE Report computed future decadal changes from a 1991 through 2000 baseline condition, whereas the change statistics reported here were computed between the observed record and the Study period of 2011 through 2060. Therefore, results of the Study and those in the SECURE Report are not identical.

5.3 Summary of *Technical Report C – Water Demand Assessment*

Four water demand storylines were developed using the scenario planning approach previously described. This section summarizes the quantification of the six scenarios resulting from those storylines and the resulting range of potential future demand in the Basin.

5.3.1 Objective and Approach

The Water Demand Assessment examined the quantity and location of current and future water demands in the Study Area. These water demands were derived from Basin resource needs, including M&I use, hydropower generation, recreation, and fish and wildlife habitat. In addition, losses in the Study Area from evaporation and other factors were assessed. Because future water supply and demand throughout the Basin are uncertain, scenarios were developed that are sufficiently broad to span that uncertainty, including the potential effects of future climate change.

Future demands are a function of socioeconomic parameters such as future population, irrigated land area, M&I and agricultural water use efficiency, tribal water use, energy production growth and associated water use, and others. Through the scenario planning process applied in the Study, the most critical uncertainties affecting future demand were identified, and a range of future demand scenarios was envisioned. Narrative descriptions of these scenarios (storylines) were developed and provide a rational basis for consideration of a wide array of future conditions. These storylines and their associated themes are:

- Current Projected (A): Growth, development patterns, and institutions continue along recent trends
- Slow Growth (B): Slow growth with emphasis on economic efficiency

- Rapid Growth (C1 and C2): Economic resurgence (population and energy) and current preferences toward human and environmental values
- Enhanced Environment (D1 and D2): Expanded environmental awareness and stewardship with growing economy

Under the storylines, two logical branches or directions were considered for the Rapid Growth (slower technology adoption—C1 and rapid technology adoption and increase in social values—C2) and Enhanced Environment (current growth trend—D1 and higher growth and technology—D2) scenarios. For example, population growth or increasing energy needs and subsequent water demand could be offset by associated technological innovations influencing water use. The four storylines, two with branches, resulted in six water demand scenarios. Complete narrative descriptions of the scenarios (storylines) are presented in *Technical Report C – Water Demand Assessment, Appendix C14 – Water Demand Scenario Storylines.*

The process to develop the critical uncertainties and demand storylines, and quantify scenarios, engaged a wide array of stakeholders and reflects a broad range of plausible conditions considering differing views of the future. In order to establish a solid foundation relating to methods and assumptions for quantifying future demands, the Study focused initial efforts on quantifying the Current Projected (A) scenario. The Current Projected (A) scenario provided the basis for consideration of departures from these assumptions, leading to the quantification of the Slow Growth, Rapid Growth, and Enhanced Environment demand scenarios. Each of the scenarios was quantified through significant input from the Basin States, with additional input provided by tribes, U.S. Fish and Wildlife Service personnel, and conservation organizations. Demand for each scenario was quantified by estimating values for individual parameters (such as population, irrigated acreage, water use efficiencies) associated with storylines and specific scenario assumptions.

Table 4 presents the demand categories, their definitions, and associated parameters collected or developed for the Study. As part of the scenario quantification process, general relationships were used to relate the expected changes in parameters for each scenario in comparison to the Current Projected (A) scenario consistent with each storyline.

Future demands may be affected by climate change, primarily changes in ambient temperature and the amount and distribution of precipitation. As such, the possible effects of changing temperature and precipitation on evapotranspiration, which may affect agriculture and outdoor M&I demand, and effects on phreatophyte and reservoir evaporation losses were also assessed in the Study. The potential impacts to evapotranspiration rates affecting agricultural demand were assessed using the Penman-Moteith method to estimate potential evapotranspiration (PET) under varying climatic conditions.

TABLE 4
Definition of Demand Categories and Their Associated Parameters

Demand Category	Definition	Parameters
Agriculture	Water used to meet irrigation requirements of agricultural crops, maintain stock ponds, and sustain livestock	Irrigated acreage, irrigation efficiency
M&I	Water used to meet urban and rural population needs, and industrial needs within urban areas	Population, population distribution, M&I water use efficiency, consumptive use factor
Energy	Water used for energy services and development	Water needs for energy generation
Minerals	Water used for mineral extraction not related to energy services	Water needs for mineral extraction
Fish, Wildlife, Recreation[1]	Water used to meet National Wildlife Refuge, National Recreation Area, state park, and off-stream wetland habitat needs	Institutional and regulatory conditions, social values affecting water use, Endangered Species Act-listed species needs, and ecosystem needs
Tribal	Water used to meet tribal needs and settlement of tribal water rights claims	Tribal use, settlements, and claims

[1] This demand category represents the consumptive use portion of demand. Non-consumptive demands are considered in metrics, see *Technical Report D – System Reliability Metrics*.

5.3.2 Summary of Results

Historical Consumptive Use

Figures 7 and 8 present the range of historical Colorado River water consumptive use and loss compiled by basin and category. This information was compiled from Reclamation's Colorado River System Consumptive Uses and Losses Reports (CU&L Reports[11]), Reclamation's Colorado River Accounting and Water Use Reports[12], and additional input from the Basin States. The categories of consumptive uses and losses presented consist of the following: agriculture; M&I; energy; minerals; fish, wildlife, and recreation; exports; reservoir evaporation; and other losses.

There are data and methodological inconsistencies in the CU&L Reports with respect to the Lower Basin tributaries (the Little Colorado, Virgin, Bill Williams and Gila rivers). These inconsistencies are primarily the result of changing methodologies between the 5-year reporting periods. Similar inconsistencies were found in these reports with respect to the Upper Basin until Reclamation undertook a multi-year effort to resolve them. This effort has not occurred for the Lower Basin tributaries, and the quality of information has suffered. Independent of the Study, Reclamation will engage in efforts to resolve and correct, in collaboration with the Basin States, the methodological and data inconsistencies in the CU&L Reports pertaining to all of the Lower Basin tributaries. Refer to *Technical Report C – Water Demand Assessment, Appendix C11 –*

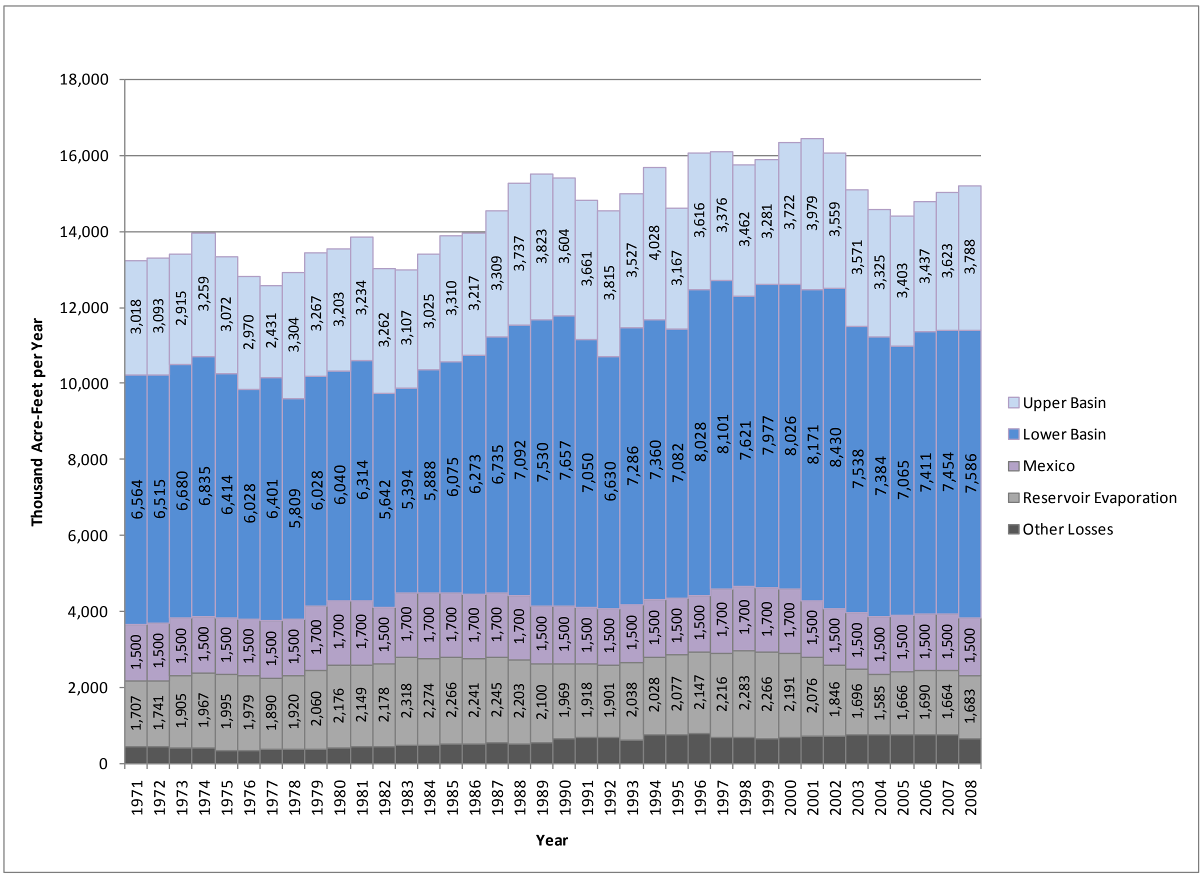
[11] Some states produce independent estimates of consumptive uses and losses. For consistency, the analysis of historical consumptive uses and losses in the Study was based on Reclamation's CU&L Reports, available at http://www.usbr.gov/uc/library/envdocs/reports/crs/crsul.html.

[12] http://www.usbr.gov/lc/region/g4000/wtracct.html.

Modeling of Lower Basin Tributaries in the Colorado River Simulation System, for a description of these issues and commitments.

Consumptive uses and losses in the Basin increased from 1971 to the start of the drought that began in 2000. The information presented in figure 7 indicates that from 1971 through 1999, Basin-wide consumptive uses and losses (including deliveries to Mexico pursuant to the 1944 Treaty[13]) have grown from approximately 13 maf in 1971 to 16 maf in 1999, an increase of about 23 percent. Over the same period, Upper Basin uses have grown from approximately 3.0 maf in 1971 to 3.3 maf in 1999, an increase of about 10 percent. Lower Basin uses have grown from approximately 6.6 maf in 1971 to 8.0 maf[14] in 1999, an increase of about 21 percent.

FIGURE 7
Historical Colorado River Water Consumptive Use[1] by Basin,[2] Delivery to Mexico, Reservoir Evaporation, and Other Losses,[3] 1971–2008



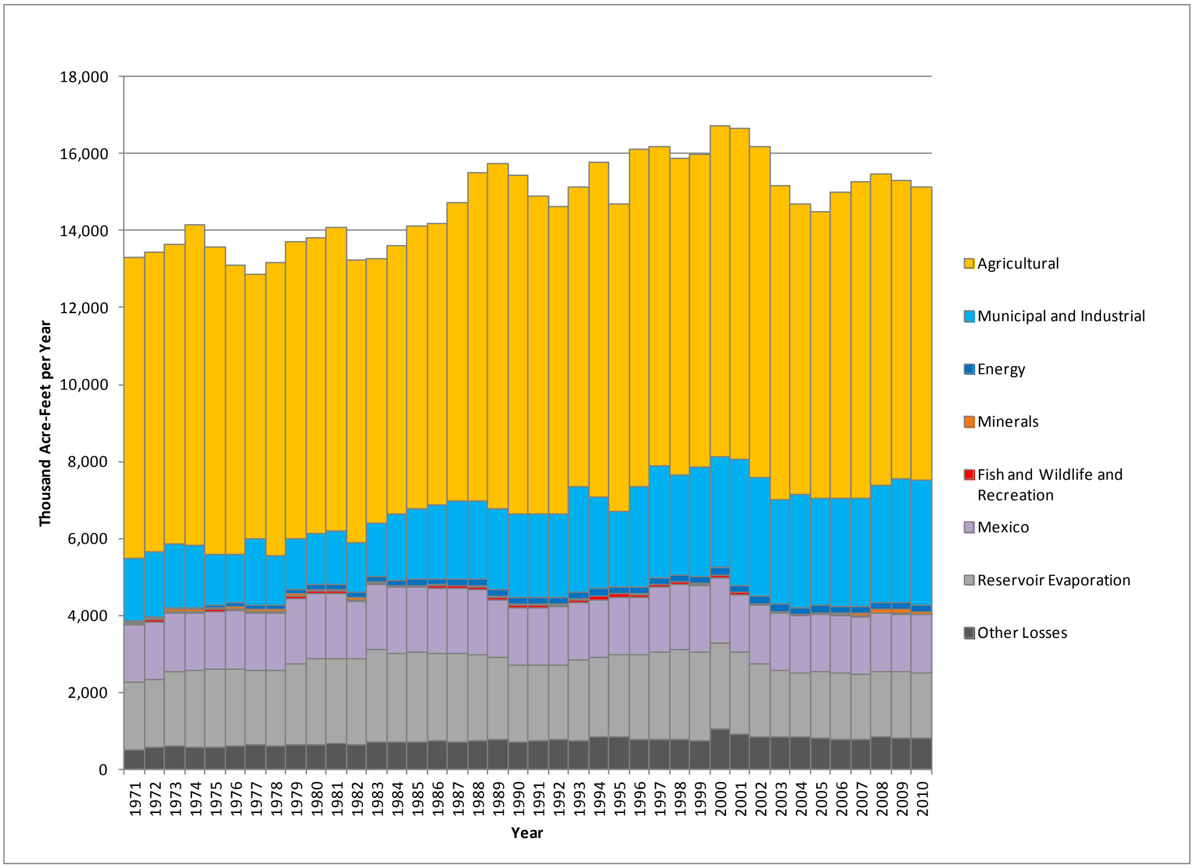
[1] Excluding consumptive use in Lower Basin tributaries.
[2] Uses in the Lower Division States greater than 7.5 maf occur during Surplus Conditions.
[3] Phreatophyte and operational inefficiency losses.

---

[13] Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande, Treaty between the United States and Mexico, 1944.

[14] Uses in the Lower Division States greater than 7.5 maf occur during Surplus Conditions.

FIGURE 8
Historical Colorado River Water Consumptive Use[1] by Use Category,[2] Delivery to Mexico, Reservoir Evaporation, and Other Losses,[3] 1971–2010



[1] Excluding consumptive use in Lower Basin tributaries.

[2] Reservoir evaporation losses are accounted differently in the Upper and Lower Basin. In the Upper Basin, reservoir evaporation losses are accounted as part of each state's total uses. In the Lower Basin, reservoir evaporation losses are accounted separately from each state's uses. Reservoir evaporation losses from Upper and Lower Basin reservoirs have been aggregated for this presentation.

[3] Phreatophyte and operational inefficiency losses.

Agricultural and M&I uses have grown over this period, as have reservoir evaporation losses. As shown in figure 8, agricultural uses have grown from approximately 7.7 maf in 1971 to 8 maf in 1999, an increase of about 4 percent. M&I uses have grown from approximately 1.4 maf in 1971 to 2.2 maf in 1999, an increase of about 57 percent. Reservoir evaporation losses have grown from 1.7 maf in 1971 to 2.3 maf in 1999, an increase of 35 percent.

In the assessment of the possible impacts to agricultural demands due to changes in precipitation and temperature, agricultural water demands are assumed to increase by approximately 5 percent for each Celsius degree increase in temperature, and by approximately 1 percent for each 5 percent reduction in precipitation.

Future Projected Demand

The quantification of the Current Projected (A) scenario was used as a starting point for the quantification of the remaining scenarios. Historical consumptive use and loss information was used in conjunction with future planning data (e.g., land use, policy, population growth, economic conditions) to inform the development of future projected demand. Although current projections are not direct mathematical projections of historical data, the Current Projected (A) scenario in particular relies on knowledge of the historical consumptive uses and losses, as described above, as well as planning data and expertise to estimate future trends in water demands. General relationships were used to relate the expected changes in parameters for each scenario in comparison to the Current Projected (A) scenario consistent with each storyline. These are shown conceptually in table 5.

Table 6 presents summary results for the demand scenarios considered in the Study. The table presents agricultural and M&I demand parameters for the Study Area, which distinguishes the scenarios, the resulting Study Area demand, and finally the Colorado River demand by category. Colorado River demand is defined as Study Area demand less the demand projected to be supplied by other sources. The Study and the results presented in this report focus on the resulting Colorado River demand.

The Study Area demand ranges between 28.7 and 32.5 maf by 2060, with Colorado River demand[15] ranging between 13.8 and 16.2 maf. Some of the increase in Study Area demand is projected to be met through increases in other supplies, primarily in Colorado and California. The increase in Colorado River demand from 2015 through 2060 is estimated to be between 1.1 and 3.4 maf, with the Lower Basin making up about 60 percent of the increase. Of the total increase in Colorado River demand, for the growing categories, between 64 and 76 percent of the growth is contributed by the M&I demand category. The growth in energy, tribal, and mineral categories constitutes the remaining increase in demand.

Relative to water use across sectors, Study Area comparisons reflect differing levels of and interplay among changing societal values, economic drivers, and various types of resource constraints. An exception to this comparison is with respect to tribal demands. It was determined during the quantification process that the factors affecting tribal demands are not particularly well-represented by the driving force categories established by the Study. For the most part, tribal demands are based on quantified rights in Current Projected (A), Slow Growth (B), and Enhanced Environment (D1) scenarios, but consider additional demands beyond current settlements in the Rapid Growth (C1 and C2) and Enhanced Environment (D2) scenarios. Additionally, it is important to recognize that the quantification of water supply and demand scenarios may compare differently at state and individual planning area levels. State level demands generally follow broad identifiable trends, whereas individual planning areas consider locally relevant information, plans, timelines, and constraints.

[15] Mexico's allotment and losses such as reservoir evaporation, phreatophyte losses, and operational inefficiencies are not part of this total. These factors were included in the modeling supporting the system reliability analysis.

TABLE 5
Scenario Matrix of Typical Changes in Parameters Defined by the Water Demand Storylines
(In general, these represent parameter change from 2015, with growth as a blue "up" arrow, no change as a yellow bar, or reduction as a green "down" arrow. The size of the arrow represents larger or smaller change for a given parameter.)

	Population	M&I Per Capita Use	Self Served Industrial Demand[1]	Agricultural Irrigated Acreage	Agricultural Per Acre Delivery	Energy Water Demand	Minerals Demand	Fish, Wildlife, Recreation Demand	Tribal Demand
Current Projected (A)	↑	↓	↑	↓	▬	↑	▬	▬	↑
Slow Growth (B)	↑	↓	↑	↓	↑	↑	▬	▬	↑
Rapid Growth (C1)	↑	↓	↑	↓	↑	↑	↑	▬	↑
Rapid Growth (C2)	↑	↓	↑	↓	↓	↓	↓	↑	↑
Enhanced Environment (D1)	↑	↓	↑	↑	▬	↓	↓	↑	↑
Enhanced Environment (D2)	↑	↓	↑	↑	↓	↓	↓	↑	↑

[1] Self-served industrial (SSI) demand represents the demand of industries in a given area that have water supply systems independent of municipal systems.

TABLE 6
Summary Results of Water Demand Scenario Quantification by 2060

Parameter	2015	2060 Scenario Parameters					
		A	B	C1	C2	D1	D2
Key Study Area Demand Scenario Parameters							
Population (millions)	38.9–41.1	62.4	49.3	76.5	76.5	62.4	76.5
Change in per capita water usage (%), from 2015	–	-9%	-7%	-9%	-16%	-19%	-17%
Irrigated acreage (millions of acres)	5.4–5.5	5.1	5.2	4.6	4.6	5.0	5.0
Change in per-acre water delivery (%), from 2015[1]	–	+1%	+2%	+1%	+3%	0%	+3%
Study Area Demand (maf)							
Agricultural Demand	16.4–16.7	15.2	15.7	13.7	13.8	14.9	14.9
M&I Demand	8.4–8.8	12.5	10.2	15.1	13.9	11.0	13.7
Energy Demand	0.34–0.63	0.66	0.57	1.01	0.58	0.51	0.56
Minerals Demand	0.1–0.11	0.18	0.18	0.22	0.15	0.15	0.15
Fish, Wildlife, and Recreation Demand	0.16–0.23	0.08	0.08	0.08	0.10	0.16	0.16
Tribal Demand[2]	1.6–1.8	2.0	2.0	2.4	2.4	2.0	2.4
Total Study Area Demand[3]	**27.3–27.8**	**30.6**	**28.7**	**32.5**	**30.9**	**28.7**	**31.9**
Colorado River Demand (maf)							
Agricultural Demand	7.1–7.2	6.7	6.8	6.6	6.7	6.6	6.8
M&I Demand	3.4–3.5	5.1	4.5	6.2	5.2	4.8	5.4
Energy Demand	0.21–0.23	0.44	0.38	0.74	0.37	0.34	0.35
Minerals Demand	0.09–0.11	0.17	0.18	0.21	0.14	0.14	0.14
Fish, Wildlife, and Recreation Demand	0.15–0.21	0.06	0.07	0.06	0.08	0.15	0.15
Tribal Demand[2]	1.5–1.7	2.0	1.9	2.4	2.4	2.0	2.4
Total Colorado River Demand[3]	**12.6–12.8**	**14.5**	**13.8**	**16.2**	**15.0**	**14.0**	**15.2**

[1] Does not include reductions associated with conservation and efficiency programs such as those in Imperial Irrigation District that are part of transfer and acquisition agreements.

[2] Tribal demand within the state of Colorado was included in other demand categories.

[3] Excludes Mexico's allotment and losses (reservoir evaporation, phreatophytes, and operational inefficiencies). These factors were included in the modeling supporting the system reliability analysis.

The Colorado River demand at three geographic levels is presented in figures 9 and 10. These figures show Study Area, Upper and Lower Basin, and individual state demand across all scenarios. The bars at the right in these figures show the relative contribution of each demand category to the total Colorado River demand at a point in time (2015, 2035, or 2060) in the Current Projected (A) scenario. In general, the category proportions remain relatively consistent across the scenarios. For the purposes of the Study, demand was not limited by the Law of the River apportionments. In this way, the demand for Colorado River and tributary water can be assessed in the context of overall Study Area demand and supplies available from other sources.

As shown in figure 9, the change in both magnitude and percentage of Colorado River demand varies considerably across the states. Colorado and Arizona show the greatest magnitude of overall growth in Colorado River demand from 2015 through 2060 across the scenarios, ranging between about 0.2 and 1.2 maf of increased demand by 2060 in Arizona and 0.04 and 0.64 maf in Colorado.

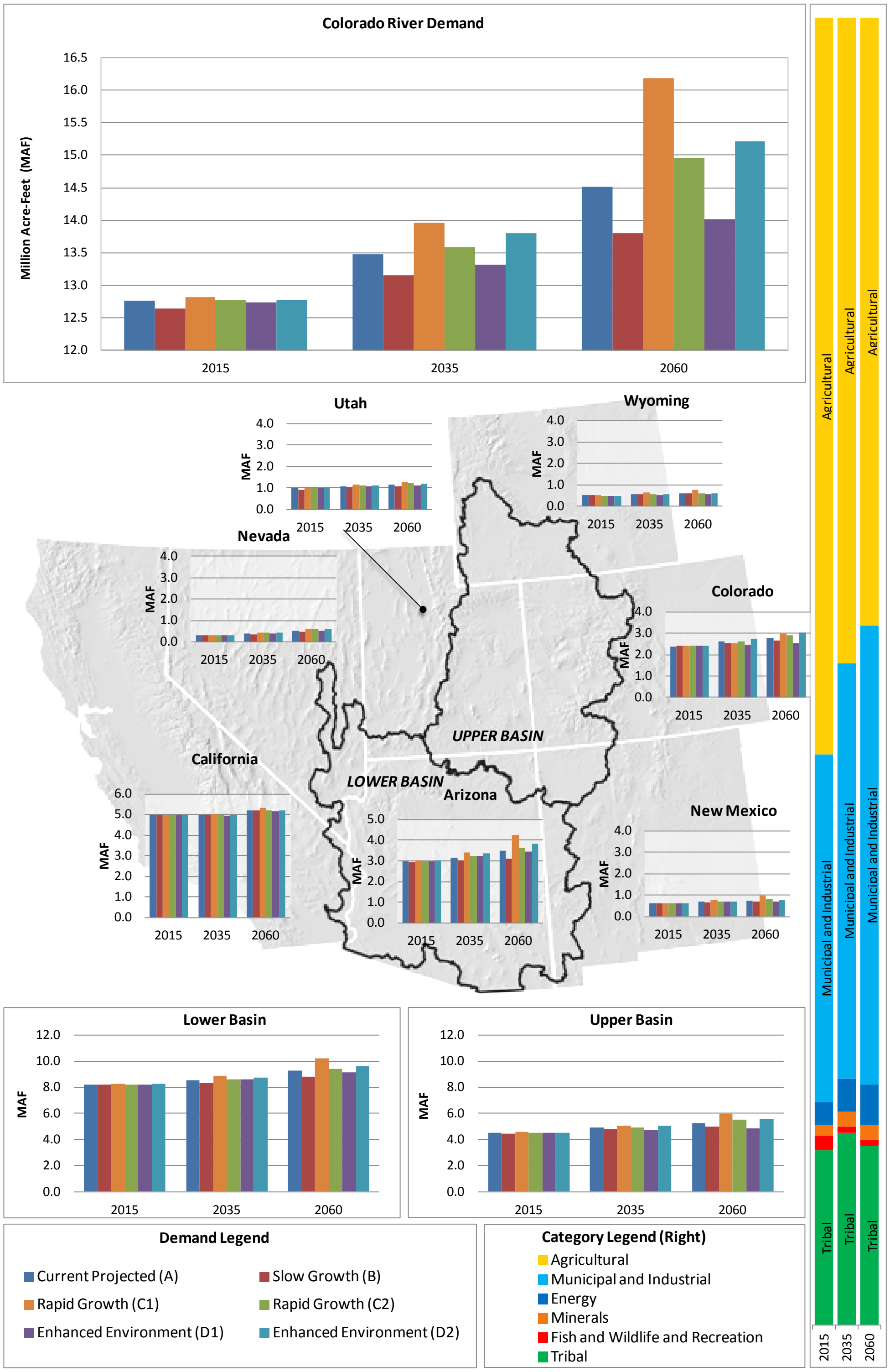
The broad demand range across scenarios in these states is due to substantial growth in M&I demand, particularly in central Arizona and the Front Range of Colorado. Increase in tribal demand is also a significant contributor to the increases in Arizona. Demand in Nevada and California is projected to increase by about 0.2 to 0.35 maf, due to population growth in Nevada and California (with supply currently limited by Colorado River Aqueduct capacity). Demand in New Mexico, Utah, and Wyoming grows by about 0.1 to 0.2 maf under most scenarios. Under the Rapid Growth (C1 and C2) scenarios, however, the growth is about 0.3 maf in Utah, where population is projected to increase by nearly 4 million and per capita water use reductions do not fully offset the rapid growth.

When demand by category is examined in figure 10, the contribution of demand by category across the Upper and Lower Basins vary, with nearly equal agricultural and M&I demand in the Lower Basin and nearly two-thirds of the demand in the Upper Basin from agriculture. The category contribution to the total demand varies considerably across states as well, with no two states having comparable proportions of categories.

Tribes hold quantified rights to a significant amount of water from the Colorado River and its tributaries (approximately 2.9 maf of annual diversion rights). In many cases, these rights are senior to other uses. Therefore, representing these rights and the associated demand is a critical component of assessing future water demand in the Basin. An additional component of future demand is an assessment of demands by tribes that have unquantified rights or claims. Where this information was provided by tribes, it was incorporated into the Study as appropriate.

Throughout the Study, Reclamation met with tribes in the Upper Basin, Lower Colorado River mainstem, and tribes served by water provided (directly or pursuant to exchanges) through the CAP facilities under contracts between tribes and the United States. In addition, Reclamation worked with the Ten Tribes Partnership, whose members have landholdings in the Upper and Lower Basins through which the Colorado River and various tributaries flow, as well as the Inter Tribal Council of Arizona, whose members are the governments of 20 tribes with land in Arizona. Based on this input, tribal demand, under all scenarios for all states (with the exception of Colorado, where tribal demand was not separated from other demands within the state, as requested by the tribes) met or surpassed the quantified tribal right by 2060. Refer to *Technical Report C – Water Demand Assessment, Appendix C9 – Tribal Water Demand Scenario Quantification* for details of quantified rights and future projected demands by tribe.

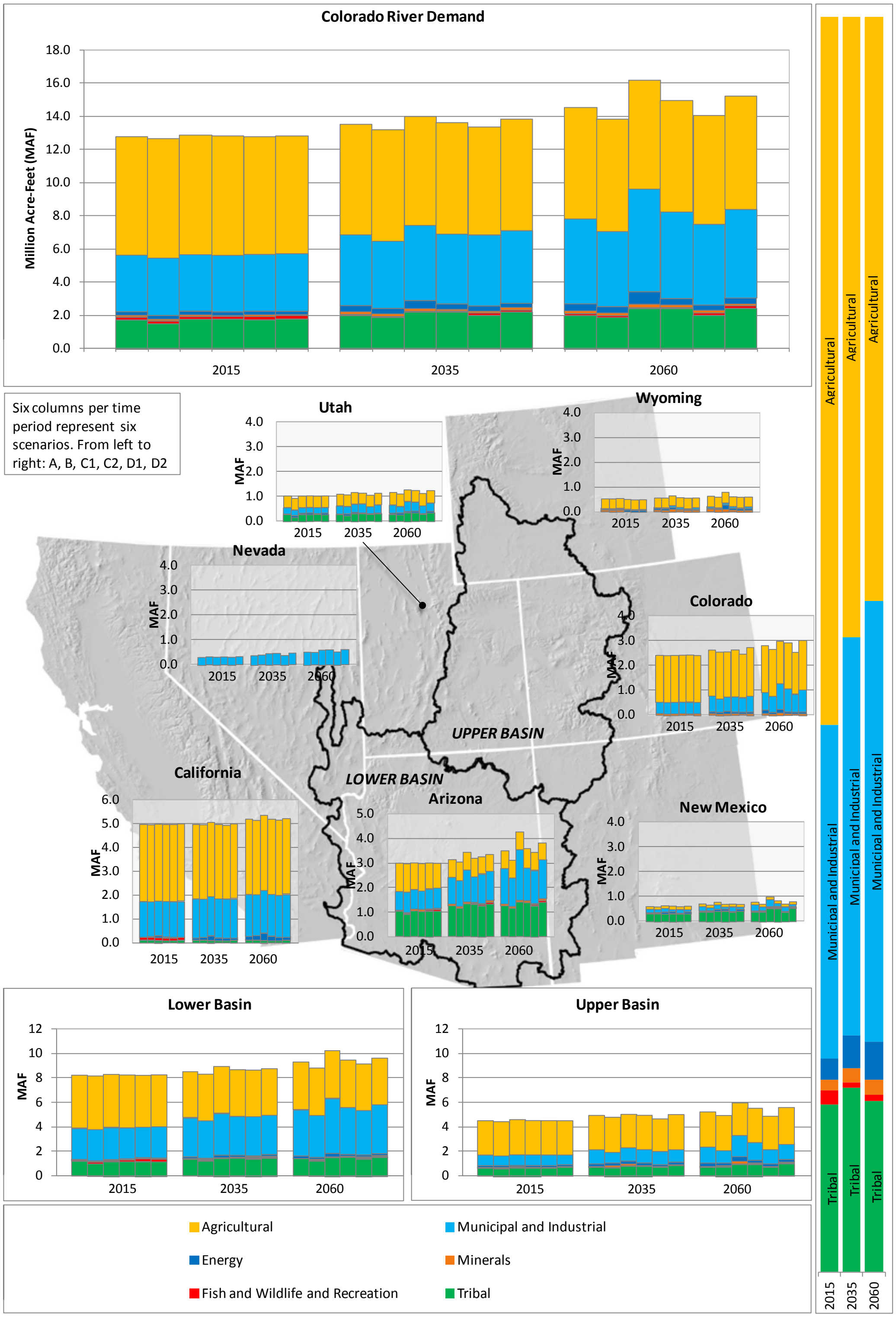
FIGURE 9
Colorado River Water Demand[1,2]



[1] Demands do not include Mexico's allotment and losses such as reservoir evaporation. These factors were included in the modeling supporting the system reliability analysis.

[2] Tribal demand in Colorado, at the request of the Southern Ute Indian and Ute Mountain Ute tribes, was not separated from other categories in the state.

FIGURE 10
Colorado River Water Demand by Category[1,2]



[1] Demands do not include Mexico's allotment and losses such as reservoir evaporation. These factors were included in the modeling supporting the system reliability analysis.

[2] Tribal demand in Colorado, at the request of the Southern Ute Indian and Ute Mountain Ute tribes, was not separated from other categories in the state.

Projected Effect of a Changing Climate on Future Demands

Future demands may be affected by a changing climate, primarily due to changes in ambient temperature and the amount and distribution of precipitation. The Study addressed possible effects of changing temperature and precipitation on evapotranspiration, which affects agriculture and outdoor M&I demand, and phreatophyte and reservoir evaporation losses. Possible changes in demand related to climate change not evaluated in the Study are changes in water demand for energy production, changes to environmental flow requirements associated with increasing ambient temperature, and changes in crop type.

As part of the hydrologic modeling for the Study, and to be consistent between the calculations used to generate water supply scenarios, a physically based method, Penman-Monteith, as implemented in the VIC model, was proposed to adjust agricultural, outdoor M&I demands, phreatophyte losses, and reservoir evaporation rates due to climate change. Details on the methods used to construct the climate index factors for adjusting demands and losses under climate change are provided in *Technical Report C – Water Demand Assessment, Appendix C15 – Climate Change Effects on Water Demand and Losses*. The mean change in evapotranspirative demand is on the order of 4 percent by 2060, compared to demands without changes in climate. A total demand increase of more than 500 kaf per year by 2060 is estimated considering potential effects of climate change. These changes will evolve over time with a warming climate, and could be higher or lower depending on the climate projection, but the magnitude of the climate impact to demands is expected to be substantial.

FIGURE 11
Current Projected (A) Scenario Demands Adjusted for Possible Future Climate Change

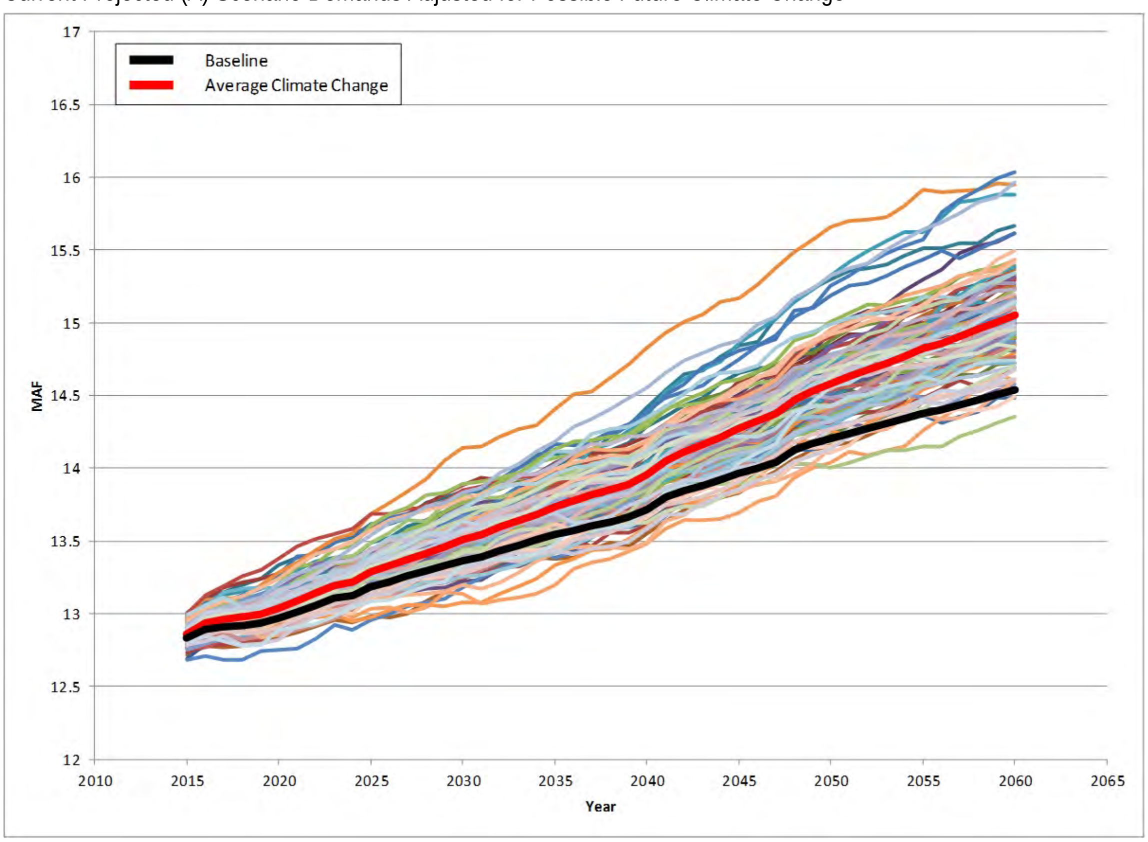
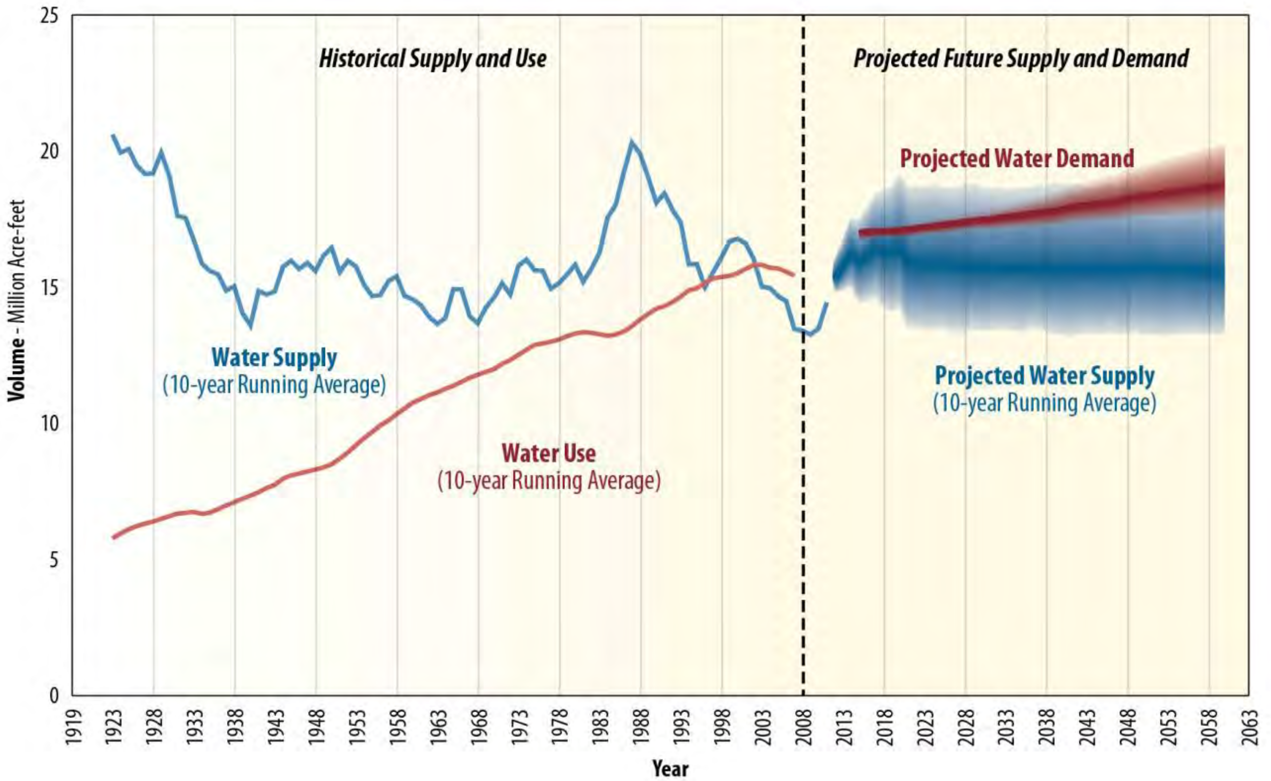


Figure 11 presents the factors as applied to the Current Projected (A) scenario demands excluding Mexico's allotment, reservoir evaporation,[16] and other losses.[17] The thick black line represents projected demand under current climate; the thick red line represents the average annual demand as adjusted for the climate change scenarios and the other lines represent individual projections of future climate.

6.0 Projected Future Supply and Demand Imbalances and System Reliability Metrics

Using the projections of future water supply and demand identified through the scenario development and quantification process, the range of the projected total future supply and demand in the Basin is shown conceptually in figure 12. Although a range of future imbalances is plausible, when comparing the median of water supply projections to the median of the water demand projections, the long-term imbalance in future supply and demand is projected to be about 3.2 maf by 2060.

FIGURE 12
Historical Supply and Use[1] and Projected Future Colorado River Basin Water Supply and Demand[1]



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

[16] Climate change effects on reservoir evaporation are adjusted dynamically through CRSS simulations.

[17] Phreatophytes are included in the "other losses" category. Losses due to phreatophytes are adjusted for climate change using similar methods as those proposed for agricultural irrigation.

It is important to recognize two points concerning this result. First, the 3.2 maf imbalance is based on the median imbalance for a particular year and can either be more or less from year to year under any one of the projections. Second, single-year imbalances of this magnitude have occurred several times in the past. Although there have been shortages in supply in Upper Basin tributaries, Colorado River deliveries of basic apportionments in the Lower Basin have been made with 100 percent reliability, primarily as a result of the ability to capture water in system reservoirs during high-flow years and to deliver that water during low-flow years. The system reliability analysis entailed simulating the operation of the system, including the effects to reservoir storage, and provides detailed information regarding the specific timing and magnitude of potential imbalances and how the Basin resources may be affected. System reliability metrics, summarized in the following section, are measures that indicate these impacts.

6.1 Summary of *Technical Report D – System Reliability Metrics*

System reliability metrics are measures that indicate the ability of the Colorado River system to meet Basin resource needs under multiple future conditions. These metrics were used to measure the potential impacts to Basin resources from future supply and demand imbalances and to measure the effectiveness of options and strategies to address those imbalances.

6.1.1 Objective and Approach

A seven-step process was adopted to develop the metrics used in the system reliability analysis. This process is detailed in *Technical Report D – System Reliability Metrics*, particularly figure D-1. The process for developing system reliability metrics began with the identification of resource categories. Based on the *Plan of Study* (see appendix 1) and working closely with stakeholders through the Metrics Sub-Team, six resource categories were identified. Following the identification of the resource categories, several attributes of interest associated with each resource category were identified.

6.1.2 Summary of Results

Table 7 presents the six resource categories and corresponding attributes of interest. To further define system reliability metrics associated with attributes of interest, locations in the Basin were selected where metrics could offer information about the performance of the system. Metrics were evaluated in either a quantitative or qualitative fashion. A metric was evaluated quantitatively if: (a) direct evaluation was possible using output from CRSS or results from post-processing of CRSS output data, or (b) an indirect indicator of the attribute of interest at the specified location could be developed, based on output from CRSS or post-processing of CRSS output data.

The ability to assess impacts to Basin resources was limited by the spatial and temporal detail of CRSS. In these cases, system reliability metrics were either assessed in a qualitative manner or, where time and resources permitted, additional analysis was conducted to result in a quantitative assessment. The map in figure 13 displays the Study Area and denotes the locations of the metrics that were defined. The locations of the water deliveries metrics were not included because there were more than 200 locations throughout the Study Area, though the primary locations used in the system reliability analysis were deliveries to the Upper and Lower Basins.

TABLE 7
Resource Categories and Attributes of Interest

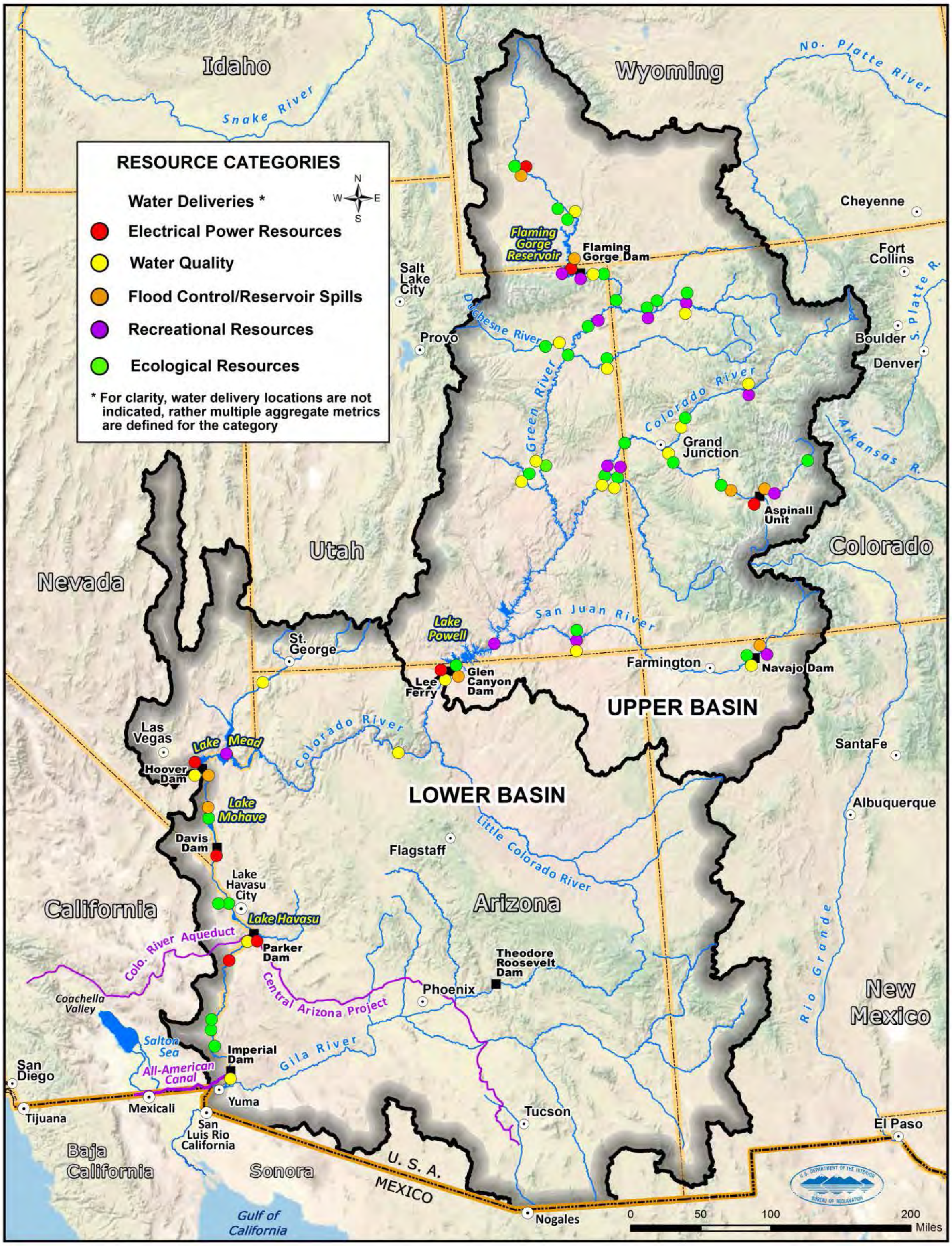
Resource Category	Attribute of Interest
Water Deliveries	• Consumptive Uses and Shortages • Water Levels Related to Intake Facilities • Socioeconomic Impacts Related to Shortages
Electrical Power Resources	• Electrical Power Generated • Economic Value of Electrical Power Generated • Available Generation Capacity • Impact on Power Rates
Water Quality	• Salinity • Sediment Transport • Temperature • Other Water Quality Attributes • Socioeconomic Impacts Related to Salinity
Flood Control	• Flood Control Releases and Reservoir Spills • Critical River Stages with Flooding Risk
Recreational Resources	• Shoreline Public Use Facilities • River and Whitewater Boating • Other Recreational Attributes • Socioeconomic Impacts Related to Recreation
Ecological Resources	• Threatened and Endangered Species • Aquatic and Riparian Habitats • Wildlife Refuges and Fish Hatcheries

7.0 Options and Strategies to Resolve Supply and Demand Imbalances

In November 2011, the Study began its fourth and final phase: Development of Options and Strategies to balance supply and demand. From November 2011 through February 2012, input was solicited from Study participants, interested stakeholders, and the general public on options and strategies for helping to resolve future water supply and demand imbalances in the Basin. Over this period over 150 options were submitted to the Study.

This section describes the options that were received, the evaluation of those options, and the development of portfolios or packages of options that reflect different strategies for resolving future imbalances.

FIGURE 13
Study Area with Locations of Defined Metrics



7.1 Summary of *Technical Report E – Approach to Develop and Evaluate Options and Strategies*

The approach toward developing and evaluating options and strategies to balance future supply and demand is described in *Technical Report E – Approach to Develop and Evaluate Options and Strategies*. The overall approach follows the assessment of plausible future water supply and demand scenarios described in Technical Reports A, B, and C, and the identification of system reliability metrics described in Technical Report D. The following steps were undertaken in this approach:

- Evaluation of system reliability without options and strategies
- Characterization of system vulnerabilities
- Identification and characterization of options
- Development of portfolios of options
- Evaluation of system reliability with options and strategies

This approach consisted of a structured process for evaluating system reliability across the range of resources metrics, identifying options that could improve the reliability, development of combinations of options based on particular response strategies (portfolios), and evaluation of the improved system reliability with the application of these portfolios. The steps involving the evaluation of system reliability and vulnerability analysis are further outlined in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*. The steps involving the identification and characterization of options and the development of portfolios are described in *Technical Report F – Development of Options and Strategies.*

7.2 Summary of *Technical Report F – Development of Options and Strategies*

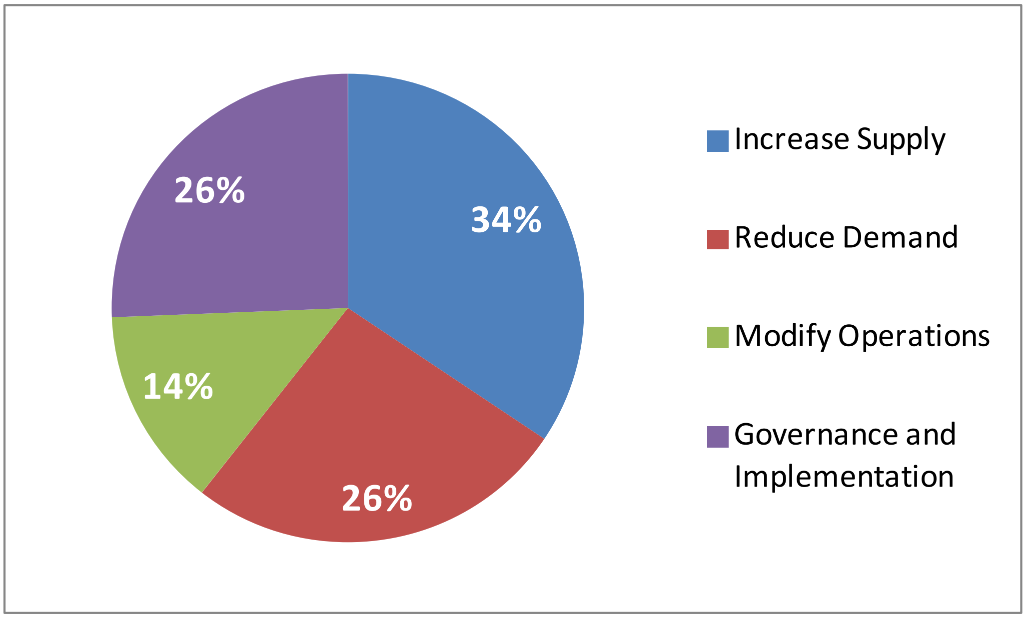
The general approach for the development of options and strategies involved the following steps: (1) soliciting input on options for consideration in order to examine a broad range of potential options, (2) organizing options into common types, (3) developing representative options from the pool of submitted options, (4) characterizing options using a set of 17 criteria that reflected a broad set of attributes of interest, and (5) developing portfolios that represent potential strategies to address future supply and demand imbalances. Details of the process and results for each of the steps are described in *Technical Report F – Development of Options and Strategies* and summarized below.

7.2.1 Summary of Options Received

Options received were organized into four types: (1) those increasing Basin water supply, (2) those reducing Basin water demand, (3) those modifying operations, and (4) those focusing on Basin governance and implementation.

A total of 55 options were submitted related to increasing supply, 42 options related to reducing demand, 22 options related to modifying operations, and 41 options related to governance and implementation. The percentage of options in each type is shown in the chart in figure 14.

FIGURE 14
Distribution of Options Received



Within each of the four option types, categories of options, such as importation, desalination, and M&I conservation, etc. were developed. Each submitted option was assigned to one category based on its primary function. From these option categories, about 40 unique representative options were described to capture the range of options submitted to and considered in the Study. Subsequent sections summarize the option categories and describe representative options that were received and considered in the Study.

7.2.2 Approach to Characterize Options

The *Plan of Study* identified specific objectives related to the development and evaluation of options. As the Study progressed, a definitive process for the characterization of options was developed. This process included the quantitative characterization of options through the assignment of ratings to a number of evaluation criteria. The process also included the qualitative characterization of options that did not directly increase supply or reduce demand. The qualitative characterization consisted of the identification of opportunities and constraints, including potential legal and regulatory issues.

Option characterization was performed to describe each of the submitted options, provide a relative comparison of the option attributes, and support the eventual development of option and portfolio evaluations. Characterization of proposed options was based primarily on information provided by the option submitter; however, existing literature and/or relevant studies also were reviewed to support the characterization process.

Characterization of the options was based on 17 evaluation criteria that are consistent with the criteria outlined in the *Plan of Study*, as summarized in table 8. These criteria are described more fully in *Technical Report F – Development of Options and Strategies*.

TABLE 8
Criteria Used to Characterize Representative Options

Criteria	Summary Description of Criteria
Quantity of Yield	The estimated long-term quantity of water generated by the option—either an increase in supply or a reduction in demand
Timing	Estimated first year that the option could begin operation
Technical Feasibility	Technical feasibility of the option based on the extent of the underlying technology or practices
Cost	The annualized capital, operating, and replacement cost per af of option yield
Permitting	Level of anticipated permitting requirements and precedence of success for similar projects
Legal	Consistency with current legal frameworks and laws, or precedent with success in legal challenges
Policy Considerations	Extent of potential changes to existing federal, state, or local policies that concern water, water use, or land management
Implementation Risk	Risk of achieving implementation and operation of option based on factors such as funding mechanisms, competing demands for critical resources, challenging operations, or challenging mitigation requirements
Long-term Viability	Anticipated reliability of the option to meet the proposed objectives over the long term
Operational Flexibility	Flexibility of option to be idled from year to year with limited financial or other impacts
Energy Needs	Energy required to permit full operation of the option, including treatment, conveyance, and distribution
Energy Source	Anticipated energy source to be used to allow option to be operational
Hydropower	Anticipated increases or decreases in hydroelectric energy generation associated with implementation of the option
Water Quality	Anticipated improvements or degradation in water quality associated with implementation of the option
Recreation	Potential impacts to recreational activities including in-river and shoreline activities
Other Environmental Factors	Other environmental considerations, such as impacts to air quality, or aquatic, wetland, riparian, or terrestrial habitats
Socioeconomics	Potential impacts to socioeconomic conditions in regions within or outside the Basin as a result of implementing the option

In general, each option was provided with a five-point rating (“A” through “E”) for each of the criteria. “A” generally represented the most favorable rating and “E” represented the least favorable.

The cost criterion includes capital and annual costs expressed in terms of unit costs in present value dollars per acre-foot. All costs presented were developed based on annualized capital costs added to annual operation and maintenance (O&M) costs divided by the annual yield of the option.

7.2.3 Summary of Option Characterization

Importation

River and other out-of-Basin freshwater imports have been proposed to increase the overall water supply of the Basin. Fifteen options related to river or other freshwater imports were received. The submitted options were reviewed and organized into three groups according to the location at which the imported water would provide water to the Colorado River or would provide exchange water for regions reliant upon Colorado River supplies.

One group consists of options for importing water from the Missouri River or Mississippi River to areas adjacent to the Basin that could use this water to meet projected shortfalls and/or reduce the amount of water these areas divert from the Basin. Water would be conveyed to the Front Range of Colorado and specific areas of New Mexico and integrated into existing water supply systems. Although these options are termed "imports," water would not actually be imported into the Basin. Rather, water would be delivered to these adjacent areas to reduce the amount of water that could be exported from the upper Colorado and San Juan rivers.

The second group of options includes diverting water from the upper headwaters of rivers adjacent to the Green River to the headwaters of the Green River. Potential sources of supply are diversions from the Bear River, upper Snake River, or Yellowstone River.

The third group consists of options that focus on importing high-quality water from other regions using ocean routes to Southern California coastal areas. Potential sources of water include the Columbia River[18], rivers in Alaska, or icebergs. Delivery mechanisms include sub-ocean pipelines for Columbia River supplies, tanker ships for Alaskan river supplies, or tug boats for icebergs. All of the options in this group require extensive transport or conveyance of water from the source regions to Southern California and require relatively complex facilities and operations to integrate the supply within the current water supply system in Southern California.

Desalination

Ocean and brackish water desalination has been proposed to increase the overall water supply of the Basin. Fifteen options related to desalination were received. The submitted options were reviewed and organized into three groups according to the source of water to be desalinated.

The first group consists of constructing new or expanding existing (or currently proposed) ocean desalination plants in strategic locations along the southern California coast or near the international boundary with Mexico. This concept also includes constructing new ocean desalination plants along the Gulf of California, Mexico. For both the Pacific Ocean and Gulf of California desalination plants, water users downstream would use desalted water in lieu of Colorado River water. Thus there would be less water diverted and/or released from Lake Havasu, the benefits of which would be seen up the river system to Lake Mead and possibly beyond to Lake Powell.

The second group of options includes constructing new diversions upstream of the Salton Sea on the New and Alamo rivers that would capture agricultural drainage water and deliver it to a regional brackish water desalination facility. The desalinated water would be delivered back to

[18] 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. This Study is not a regional or river basin plan or proposal or plan for any Federal water resource project.

the All American Canal and exchanged for an in-kind amount of reduction in diversions from the Colorado River at Imperial Dam.

The third group consists of options for desalination of brackish water in Southern California and Arizona consistent with past similar projects, and also refurbishing the Yuma Desalting Plant to allow full-scale production.

Reuse

Reuse of existing water supplies was proposed as a method of increasing overall water supply in the Basin. Eleven options were submitted related to wastewater reuse. The submitted options were reviewed and organized into three groups. Representative options were developed for each option group to represent the distinct nature of the options within each group.

The first group of options related to various methods of reuse of municipal wastewater in major urban areas. Municipal wastewater reuse considers new and expanded programs for non-potable purposes such as irrigation and also for potential potable purposes through indirect or direct methods.

The second group consisted of the reuse of industrial wastewater that is not traditionally discharged through municipal wastewater systems.

The third group consisted of reuse of grey water at individual homes or communities for non-potable purposes. Grey water is typically defined as untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes (California Building Standards Commission, 2010).

Local Supply

Developing new local supply was proposed to increase the overall water supply of the Basin. Four options related to local supply were received. The submitted options were reviewed and organized into two groups according to the source of local supply.

In the process of developing natural gas resources, poor-quality groundwater is typically "produced" from natural gas wells. The coal bed methane industry has generally disposed of produced water at the least possible cost rather than treat and use this potential resource. In most cases, coal bed methane-produced waters are disposed by injection into Class II underground injection wells. This group of options considers treating the relatively high-salinity water and using it to augment supply in the Basin.

Rainwater harvesting is the capture, diversion, and storage of rainwater for landscape irrigation and other uses. This option group considers how individual household rainwater harvesting can increase local supply throughout the Basin, with particular emphasis on those areas that do not return flows to other users downstream. Rainwater harvesting is not legally permitted in Colorado, and this state-specific issue was recognized within the Study.

Watershed Management

Changes to watershed management were proposed to increase the overall water supply of the Basin. Ten options related to watershed management were received. The submitted options were reviewed and organized into five groups according to the specific type of watershed management recommendations.

Control of invasive tamarisk has been proposed for riparian areas to reduce the overall consumptive use and increase streamflow in the Colorado River. Removal of tamarisk is proposed on riparian benches where water that would have otherwise contributed to streamflow is being consumptively used by tamarisk.

A large percentage of the runoff from the Basin is derived from forests, particularly in Colorado. Previous studies and information have demonstrated that areas in which forest cover is reduced by clear-cutting or fires have shown dramatically increased amounts of runoff. The forest management group of options would entail the replacement of mature forests that have been cleared by harvesting, fires, or insect infestations with stands of replacement growth more likely to be favorable for generating runoff.

Brush control involves reducing brush and therefore reducing consumptive use by vegetation communities. The brush control group of options recommends various techniques available for brush removal, including chemical spraying, chaining, roller chopping, root plowing, grubbing, and controlled fires.

Dust control options propose to control land-based dust sources that contribute to dust accumulation on snow, which changes the albedo, or reflectivity, of the snow resulting in earlier snowmelt (Painter et al., 2007, 2010, and 2012; Skiles et al., 2012) and more evaporative moisture losses. By implementing measures to reduce the accumulation of dust on snow, lower evaporative losses are anticipated.

Weather modification was proposed for increasing precipitation in Basin. Cloud seeding is the most prominent method considered for weather modification. In particular, the seeding of clouds with silver iodide to serve as condensation nuclei can increase snowfall over mountainous regions. Winter cloud seeding operations have been in operation throughout the West since the late 1940s. In recent years, ongoing cloud seeding operations have been documented in at least five of the seven Basin States.

Municipal and Industrial Water Conservation

Development of additional M&I water conservation was proposed to further reduce the overall M&I water demand in areas currently relying upon water supply from the Colorado River. Twenty-nine M&I conservation options were submitted for consideration in the Study, with several of the submitted options suggesting specific conservation measures.

Because levels of current and future conservation vary throughout the Study Area, different levels of potential savings are possible for a given conservation measure. These savings range from essentially no savings where measures have been fully enacted to significant savings where measures have not been enacted or where adoption rates are relatively low. Disaggregating the savings potential by conservation measure and individual location was beyond the scope of the Study. Instead, M&I conservation measures were considered for the entire Study Area with the acknowledgement that, despite state and regional differences in current levels of conservation and potential for future conservation, some additional conservation is achievable on a Study Area-wide basis.

In order to examine the potential for additional M&I conservation and to explore the range of costs and other factors, three levels of conservation were considered based on assumed levels of reductions and adoption rates for residential indoor, commercial-institutional-industrial, landscape, and water loss. Conservation considered in the demand scenarios ranged from about

300 kaf per year to more than 1.1 million acre-feet per year (mafy) in 2060, depending on the assumptions within each scenario regarding the degree of per capita water demand reductions[19]. Additional conservation beyond that included in the demand scenarios was considered in three additional conservation levels (Level 1, 2, and 3) that generate up to a range of 0.7 to 1.3 maf of additional water savings in 2060, depending on the demand scenario. The potential savings of the options would be small in the early years of implementation and grow over time.

Agricultural Water Conservation

Options were submitted proposing agricultural water conservation to reduce the overall water demand in areas currently relying upon water supply from the Colorado River. These options ranged in type from specific conservation mechanisms or best management practices (e.g., improved irrigation efficiencies, modernization, conveyance system efficiencies, changes in types of crops under irrigation) to general implementation approaches to achieve further water conservation (e.g., water pricing or water transfers).

The concepts received were first organized into six Basin-wide agricultural water conservation mechanisms that reflect different types of activities that could generate water savings in the agricultural sector. These agricultural water conservation measures consist of advanced irrigation scheduling, deficit irrigation, on-farm irrigation system improvements, controlled environment agriculture, conveyance system efficiency improvements, and fallowing of irrigated lands. Because the method of implementation is important for realization of water savings, two implementation approaches that could be used to encourage or incentivize adoption of these water conservation mechanisms were considered:

(1) ***Basin-wide agricultural conservation*** through a federal or state incentivized program to encourage agricultural water use efficiency and,

(2) ***Basin-wide agricultural conservation with water transfers*** on a willing transferor-willing transferee basis that promotes water conservation and/or short-term or permanent fallowing of irrigated lands to transfer conserved water for a similar or different use.

For purposes of the Study, each of the various conservation measures was examined as a Basin-wide potential, but in reality the measures will have important regional limitations and in some cases may be mutually exclusive. The various measures should not be considered as additive. Because the conservation measures could produce different amounts of savings depending on the location in the Basin, implementation approach, and combination of measures, the total quantities were estimated as an aggregate for each implementation approach. Up to 1 mafy of potential savings by 2060 was considered for each approach (conservation and conservation with transfers) although the approaches are not considered additive. The 1 mafy of potential savings recognizes an amount of additional water conservation above and beyond the significant existing and future water conservation programs that are already included in the Study's demand scenarios.

Energy Water Use Efficiency

Options to improve the water use efficiency of the energy sector have been proposed to reduce the water demand of the Basin. Four options related to energy water use efficiency were

[19] The level of M&I conservation included in the water demand scenarios was estimated by first re-computing the M&I demands under each scenario assuming the 2015 gallons per capita per day value from that scenario. The difference in the M&I demand in 2060 with gallons per capita per day held at 2015 levels from the M&I demand in 2060 under the actual demand scenario is the amount of M&I conservation achieved under that demand scenario.

received. The submitted options were reviewed and organized into two groups according to the different concepts proposed for reducing water demand.

The first group of options includes removing the evaporative cooling systems at the 15 largest power plants in the Basin and installing air-cooling systems. The second group of options addresses the need for a reliable water source for oil and gas development, and suggests options for ensuring sufficient supplies through a number of improved efficiency measures.

System Operations

Options dealing with modified system operations have been proposed to increase the overall water supply, decrease demand, reduce evaporation losses, and improve efficiency within the Basin. The submitted options were reviewed and organized into three option groups according to the overarching concept driving the new or modified operation.

The first group includes physical and chemical methods to reduce evaporation from the major canals and reservoirs. Physical covers would incorporate solar photovoltaic panels to simultaneously reduce evaporation and generate electricity, and concepts involving chemical covers include the introduction of a chemical to the water surface of large reservoirs to reduce the evaporation rates of the reservoirs.

The second group proposed new water storage to increase the amount of system storage available for either hydropower optimization or capture of water released but not diverted. It also included improved groundwater management.

The third group of options consists of recommendations for changing current reservoir operations in the Basin to improve water management. These options consist of reoperation to reduce reservoir evaporation, maximize hydropower generation, or improve environmental conditions.

Water Transfers, Exchanges, and Banking

Water transfers, exchanges, and banking have been proposed to increase the efficient use of existing supplies in the Basin. This group consists of options that are reflected in the following representative options: water transfers and exchanges, guided water markets, Upper Basin water banking, Lower Basin water banking, and groundwater banking.

Because of their complexity and the inability to develop representative options indicative of all water banking or transfer-type options, these options have not been assigned ratings for the 17 criteria. Water transfers and banking options generally require working in conjunction with conservation options (agricultural or M&I) in order to generate the water to be transferred or banked.

The guided water markets option would attempt a strategic, guided approach to transactions that could be used proactively to meet demand reduction goals to reduce the risk for Lee Ferry deficit. Another option proposes that a similar concept to the Intentionally Created Surplus (ICS) program in the Lower Basin be applied in the Upper Basin. This option creates an Upper Basin water bank in either Lake Powell or in an off-stream groundwater bank to increase protection against a Lee Ferry deficit in extremely dry conditions.

The 2007 Interim Guidelines (DOI, 2007) implemented an ICS mechanism to provide for the creation, accounting, and delivery of conserved system and non-system water, thereby promoting water conservation in the Lower Basin. The ICS mechanism allows for conserved water in the Lower Basin to be stored in Lake Mead for subsequent delivery in future years. Several options suggested continuing this program beyond the expiration of the 2007 Interim Guidelines in 2026 and expanding or modifying it to include participants beyond entitlement holders to Colorado River mainstem water in the Lower Basin, including Mexico[20].

Finally, some options focused on using groundwater recharge and recovery as an underground water bank. An entity could divert water to groundwater storage when there is a surplus or reduced need for surface supplies. When there is a critical or increased need for additional supply, the entity could then withdraw an equivalent amount of water that it previously banked subject to withdrawal limits. This concept is already used in several areas of the Lower Basin.

Water Management and Allocation

Options were submitted that suggested modifications to Basin water management processes and changes in the distribution of water supply available in the Basin under the Law of the River. There are four representative options in this group: changes to apportionment of water supply, processes for expanded stakeholder involvement, population control, and conservation and trust funds. These options suggested modified methods for governing or managing water supply and demand in the Basin. Although these have been included in the Study for completeness and continued dialogue, mechanisms currently exist for flexible operations without destabilizing the Law of the River or triggering lengthy legal battles that would inevitably occur with any attempt to re-allocate the river.

Tribal Water

Tribes hold quantified rights to a significant amount of water from the Colorado River and its tributaries (approximately 2.9 maf of annual diversion rights). In many cases, these rights are senior to other users. Options pertaining to water development and use were submitted by tribes for consideration in the Study and include concepts such as voluntary tribal water transfers, tribal water storage and ICS, convening of an inter-governmental forum, resolution of tribal claims, affordability of tribal water and removing barriers to tribal participation in federal programs, recognition limits to reduce demand, stabilization of soil, and development of non-tributary groundwater. Recalmation will work with tribes in future efforts regarding tribal water issues reflected in this report.

Data and Information

Options were submitted that suggested improvements to the data and information used by Reclamation for analysis and modeling. These options involved improved water use accounting in the Upper Basin and additional improvements to CRSS. Reclamation is committed to working with the Basin States, interested stakeholders, and the USGS to improve water use accounting and to refine CRSS and other supporting models where it is feasible and useful in order to provide the most realistic representation of how the system is currently operated or may be operated in the future.

Summary of Characterization Ratings

For each of the quantified options developed for the Study, characterization ratings were assigned based on the 17 evaluation criteria. The characterization provided a relative comparison of the option attributes and supported the analysis of options and development of portfolios.

---

[20] On November 20, 2012, Minute 319 was signed, which created a mechanism for Mexico to store water in Lake Mead, called Intentionally Created Mexico Allotment. This is a temporary agreement, however, and the long-term implementation of such a mechanism is subject to future Minutes.

Three of the evaluation criteria were developed with both numeric values as well as letter rating: cost, quantity of yield, and timing.

Table 9 summarizes the potential yield for each of the main option groups in 2035 and 2060. A total of 7.6 mafy of potential yield was identified for options that increase supply. The options with greatest yield of this type are related to watershed management methods, desalination of ocean and brackish water, importation, and reuse. A total of 2.2 mafy of potential savings was identified through options that reduce demand. The principal options that comprise this type are agricultural water conservation, M&I water conservation, and energy water use efficiency. Potential savings totaling 1.2 maf y were identified under the options that modify system operations and primarily reflect reducing reservoir or canal evaporation through physical or chemical covers, or through preferential reservoir storage. When considering all options and all categories by 2060, a total of over 11 mafy in potential yield was identified. The potential yield is approximately 5.7 maf y by 2035; however, not all options are equally feasible or reliable in the long term. Many options such as imports to southern California or some watershed management options are uncertain from both a technical feasibility and reliability standpoint. By excluding options that were rated low for these factors (“D” and “E”), the total potential yield was reduced to approximately 3.7 mafy by 2035 and to approximately 7 mafy by 2060.

The cost, yield, and timing of the representative options are shown in figure 15 (sorted based on cost). Some of the least-cost options are related to weather modification and chemical covers, but these have considerable uncertainty related to their long-term viability and implementation risk. Agricultural water conservation, M&I water conservation, watershed management methods, smaller import options, and brackish water desalination projects represent the next-least-expensive set of options. Larger desalination, reuse, and importation projects are estimated to have higher costs, but still be substantially less than distributed rainwater harvesting and grey water reuse options, and canal and reservoir covers.

In addition to cost, yield, and timing, each option was provided with a five-point rating (“A” through “E”) for the remaining 14 criteria. A rating of “A” generally represents the most favorable rating and “E” the least favorable. Figure 15 summarizes the resulting ratings for each of the option categories and groups. In some cases, multiple ratings are shown in this figure due to the assessment of large-scale options into smaller increments to capture the varying degree of difficulty of implementing larger options or degree of potential impacts. In general, options that improved the water use efficiency (conservation and reuse) were rated higher than other options for most of the criteria. Options such as importation, desalination, and reuse were rated favorably for technical feasibility and long-term viability risks, but less favorably for environmental criteria because of their greater energy needs and potential impacts to source or discharge areas. Most watershed management options, although potentially yielding significant new supply, were rated poorly for technical feasibility and long-term viability because of the unproven reliability of application of many of these techniques on the scale envisioned for the Basin.

TABLE 9
Summary of Option Cost and Potential Yields by 2035 and 2060

Option Category	Option Group	Estimated Cost ($/afy)	Years Before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)
Desalination	Gulf of California	2,100	20–30	200,000	1,200,000
	Pacific Ocean in California	1,850–2,100	20–25	200,000	600,000
	Pacific Ocean in Mexico	1,500	15	56,000	56,000
	Salton Sea Drainwater	1,000	15–25	200,000	500,000
	Groundwater in Southern California	750	10	20,000	20,000
	Groundwater in the Area near Yuma, Arizona	600	10	100,000	100,000
	Subtotal			**776,000**	**2,476,000**
Reuse	Municipal Wastewater	1,500–1,800	10–35	200,000	932,000
	Grey Water	4,200	10	178,000	178,000
	Industrial Wastewater	2,000	10	40,000	40,000
	Subtotal			**418,000**	**1,150,000**
Local Supply	Treatment of Coal Bed Methane-Produced Water	2,000	10	100,000	100,000
	Rainwater Harvesting	3,150	5	75,000	75,000
	Subtotal			**175,000**	**175,000**
Watershed Management	Brush Control	7,500	15	50,000	50,000
	Dust Control	220–520	15–25	280,000	400,000
	Forest Management	500	20–30	200,000	300,000
	Tamarisk Control	400	15	30,000	30,000
	Weather Modification	30–60	5–45	700,000	1,700,000
	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
	Imports to the Green River from the Bear, Snake[1], or Yellowstone Rivers	700–1,900	15	158,000	158,000
	Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River[1]	2,700–3,400	15	600,000	600,000
	Subtotal			**758,000**	**1,358,000**
M&I Water Conservation	M&I Water Conservation	500–900	5–40	600,000	1,000,000
	Subtotal			**600,000**	**1,000,000**

TABLE 9
Summary of Option Cost and Potential Yields by 2035 and 2060

Option Category	Option Group	Estimated Cost ($/afy)	Years Before Available	Potential Yield by 2035 (afy)	Potential Yield by 2060 (afy)
Agricultural Water Conservation	Agricultural Water Conservation	150–750	10–15	1,000,000	1,000,000
	Agricultural Water Conservation with Transfers	250–750	5–15	1,000,000	1,000,000
	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
	Subtotal			**160,000**	**160,000**
System Operations	Evaporation Control via Canal Covers	15,000	10	18,000	18,000
	Evaporation Control via Reservoir Covers	15,000	18	200,000	200,000
	Evaporation Control via Chemical Covers on Canals and Reservoirs	100	15–25	200,000	850,000
	Modified Reservoir Operations	Unknown	15	0 – 300,000	0 - 300,000
	Construction of New Storage	2,250	15	20,000	20,000
	Subtotal			**588,000**[3]	**1,238,000**[3]
	Total of All Options			**5,735,000**[4]	**11,037,000**[4]

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

7.2.4 Development of Portfolios

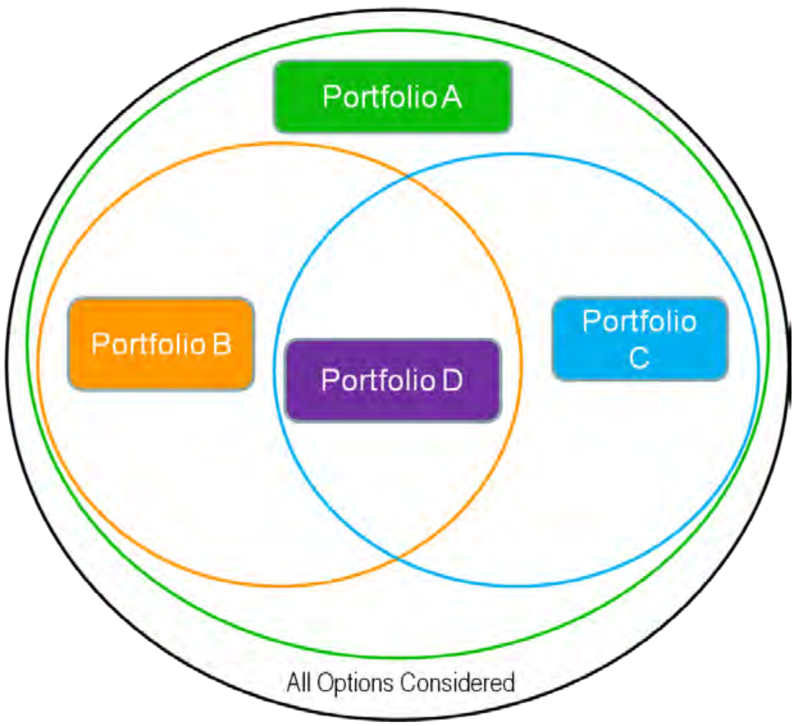
Based on the results of the characterization and development of representative options, various representative options were combined into portfolios representing different potential adaptation strategies. The Study developed four exploratory portfolios to reflect different strategies for selecting and combining options to address imbalances between water supply and water demand. Each portfolio consists of a unique selection of options to address vulnerabilities (e.g., declining Lake Mead pool elevation) that may exist under future combinations of supply and demand.

FIGURE 15
Summary of Options Characterization Ratings (aggregated by option groups)

Agricultural (Ag), Upper Basin (UB), Lower Basin (LB), Municipal and Industrial (M&I), Modification (Mod), Desalination (Desal), Southern California (SoCal)

Using the ratings associated with the criteria, preferences were expressed that resulted in two portfolios, *Portfolio B* and *Portfolio C*. Two other portfolios were then added, *Portfolio A* which represents a highly inclusive strategy (includes all options in either *Portfolio B* or *Portfolio C*) and *Portfolio D*, which represents a highly selective strategy (includes only options in both *Portfolio B* and *Portfolio C*). *Portfolio B* includes options with high technical feasibility and long-term reliability, but excludes options with the highest permitting, legal, policy, or long-term viability risks. *Portfolio B* also excludes any options that cost more than $2,500 per af. *Portfolio C* focuses on options that are also highly feasible, but excludes options that could have greater environmental impacts. This portfolio excludes options that cost more than $4,200 per af. The schematic in figure 16 shows the relationships of the options included in the Study portfolios.

FIGURE 16
Schematic Representing Options Included in the Study Portfolios



Portfolio A
Portfolio A includes options with high technical feasibility, excludes options with highest permitting, legal, policy, and long-term viability risks. This portfolio includes options that are included in both *Portfolio B* and *Portfolio C*. This portfolio also includes the Upper Basin water bank concept that is described in *Portfolio C*. *Portfolio A* includes the largest number of options and option types of the four portfolios. This portfolio is the least restrictive in terms of options.

Portfolio B
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 one that seeks options with proven technology and that, once in place, will produce reliable long-term yield. The strategy represents a low-risk strategy in the long-term,

but may consider greater risk with respect to permitting and implementation. However, this portfolio excludes options with the highest permitting, legal, and policy risks. The portfolio includes a blend of options that increase supply and those that decrease demand. Water conservation and a variety of desalination options are included in the near-term (first 25 years) and imports and expansion of reuse programs dominate the longer-term options.

Portfolio C
Portfolio C focuses on options that are technically feasible but also have low environmental impacts—low energy needs, lower carbon energy sources, low permitting risk, and low impacts to other environmental factors. This portfolio also avoids options that are potentially unfavorable to recreational interests. In addition, this portfolio excludes options with the highest permitting, legal, and policy risks. The portfolio includes significant conservation in the near term and relies on reuse and watershed management rather than desalination and imports to augment supplies in the longer-term. In addition to options that either reduce demand or increase supply, the portfolio also includes a mechanism to transfer water conserved in Upper Basin through M&I, agricultural water conservation, and energy water use efficiency, to a conceptual Upper Basin water bank. Water is stored in the water bank until needed to be released in order to avoid Lee Ferry deficit[21] conditions.

Portfolio D
Portfolio D includes only those options included in both *Portfolio B* and *Portfolio C*. Significant options not included in this portfolio are several desalination options and imports from the Missouri River. In addition to containing less potential yield than other portfolios, *Portfolio D* also includes the fewest number of options.

In developing each of the unique portfolios, a set of preferences regarding the characteristics of options, as defined by the criteria ratings, was defined. These preferences defined the particular strategy of the portfolio. The Options and Strategies Sub-Team assisted in the development of the four portfolios by identifying general strategies, option criteria preference sets, and reviewing draft portfolios. Adjustments to portfolios were made to either include or exclude specific options or to specify that an option is to be implemented as soon as available based on input from the Options and Strategies Sub-Team members. The option criteria preferences included in each portfolio are shown in table 10.

7.2.5 Portfolio Comparison

The four portfolios represent different exploratory approaches for addressing the projected imbalances between water supply and demand. These portfolios were developed in conjunction with the Options and Strategies Sub-Team, but should not be considered as individual suggestive pathways. Rather, they were developed to explore the range of options, different preferences for option characteristics, and different levels of option inclusion. Table 11 provides a high-level comparison of the options that were either included in all portfolios, included in some but not all portfolios, and those options that were not included in any portfolio. As the table shows, high levels (above 400 kaf) of Gulf of California and Pacific Ocean desalination options, the most complex import options, reservoir and canal covers, and many of the watershed management

[21] 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.

options were not selected for inclusion in any of the portfolios. Only 12 options are included in some but not all portfolios. These included ocean desalination options, imports from the Missouri River, expensive options related to local distributed supply or reuse development such as rainwater harvesting and grey water reuse, and watershed management options such as tamarisk control and dust management.

TABLE 10
Option Criteria Preferences for the Study Portfolios

Criteria Category	Option Criteria	Portfolio			
		Portfolio A	Portfolio B	Portfolio C	Portfolio D
Technical	Technical Feasibility	Excludes D & E	Excludes D & E	Excludes D & E	Excludes D & E
	Implementation Risk	All	All	All	All
	Long-term Viability	Excludes E	Excludes D & E	Excludes E	Excludes D & E
	Operational Flexibility	All	All	All	All
Environmental	Permitting	Excludes E	Excludes E	Excludes D & E	Excludes D & E
	Energy Needs	All	All	Excludes D & E	Excludes D & E
	Energy Source	All	All	Excludes E	Excludes E
	Other Environmental Impacts	All	All	Excludes D & E	Excludes D & E
Social	Recreation	All	All	Excludes D & E	Excludes D & E
	Legal	Excludes E	Excludes E	Excludes E	Excludes E
	Policy	Excludes E	Excludes E	Excludes E	Excludes E
	Socioeconomics	All	All	All	All
Other	Hydropower	All	All	All	All
	Water Quality	All	All	All	All
	Cost	< $4,200/af	< $2,500/af	< $4,200/af	< $2,500/af

A rating of "A" generally represents the most favorable rating and "E" the least favorable. For example, a rating of "E" for technical feasibility indicates those options with the lowest scoring in terms of feasibility. A rating of "E" for permitting indicates those options with extremely challenging permitting requirements.

TABLE 11
Summary of Option Inclusion Across the Study Portfolios

Option Category	Option Group	Portfolios			
		Portfolio A	**Portfolio B**	**Portfolio C**	**Portfolio D**
Importation	Imports to the Colorado Front Range from the Missouri or Mississippi Rivers	X	X		
	Imports to the Green River from the Bear, Snake, or Yellowstone Rivers				
	Imports to Southern California via Icebergs, Waterbags, Tankers, or from the Columbia River				
Desalination	Gulf of California	Up to 400 kaf	Up to 400 kaf		
	Pacific Ocean in California	Up to 400 kaf	Up to 400 kaf		
	Pacific Ocean in Mexico	X	X		
	Salton Sea Drainwater	X	X	X	X
	Groundwater in Southern California	X	X	X	X
	Groundwater in the Area near Yuma, Arizona	X	X	X	X
Reuse	Municipal Wastewater	X	X	X	X
	Grey Water	X		X	
	Industrial Wastewater	X	X	X	X
Local Supply	Treatment of Coal Bed Methane-Produced Water	X	X		
	Rainwater Harvesting	X		X	
Watershed Management	Brush Control				
	Dust Control	X		X	
	Forest Management				
	Tamarisk Control	X		X	
	Weather Modification	Up to 300 kaf	Up to 300 kaf	Up to 300 kaf	Up to 300 kaf
M&I Water Conservation	M&I Conservation	X	X	X	X
Agricultural Water Conservation	Agricultural Water Conservation				
	Agricultural Water Conservation with Transfers	X	X	X	X

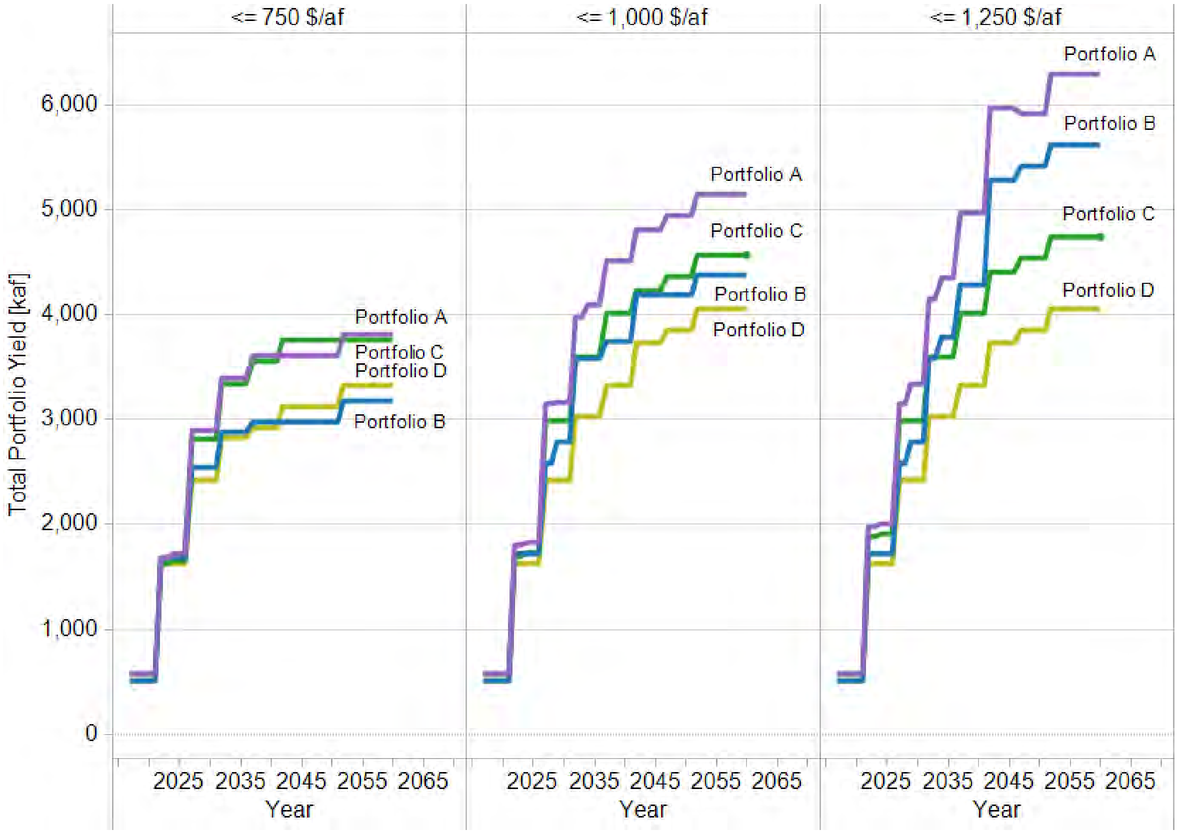
TABLE 11
Summary of Option Inclusion Across the Study Portfolios

Option Category	Option Group	Portfolios			
		Portfolio A	Portfolio B	Portfolio C	Portfolio D
Energy Water Use Efficiency	Power Plant Conversion to Air Cooling	X	X	X	X
System Operations	Evaporation Control via Canal Covers				
	Evaporation Control via Reservoir Covers				
	Evaporation Control via Chemical Covers on Canals and Reservoirs				
	Modified Reservoir Operations				
	Construction of New Storage				
Water Banking	Upper Basin Water Bank	X		X	

The differences in the selection or inclusion of options in the portfolios also influenced the total potential yield and implementation cost. Figure 17 shows the potential yield of the four portfolios over time for three different limits on the portfolio average cost. On the right, the portfolios are essentially unconstrained by cost (average costs less than $1,250 per af). Not surprisingly, *Portfolio A* has the highest potential yield (~6.3 maf) and *Portfolio D* has the lowest potential yield (~4.0 maf). *Portfolio B* and *Portfolio C* yields are similar through 2042. At that point, *Portfolio B* yield increases significantly more than *Portfolio C*. For lower average costs, the differences between the four portfolios are less significant (figure 17, left and middle), particularly between *Portfolio B* and *Portfolio C*.

The four portfolios considered in the Study represent different potential strategies for dynamically addressing system vulnerabilities that may develop in the future. Because there are many more strategies than could be evaluated in the Study, the portfolios should be considered exploratory. The primary focus of the portfolio development and subsequent evaluation in the Study was to establish the range of responses, types of options that may be considered for implementation, their effectiveness at addressing vulnerabilities, and the range of cost and other attributes resulting from different portfolio implementations.

FIGURE 17
Total Yields over Time for Average Costs less than $750/af (left), less than $1,000/af (middle), and less than $1,250/af (right) for Portfolios



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

Potential future Basin supply and demand imbalances suggest that some course of action will be required to improve the reliability of the system to meet the stresses on the Basin resources. From solicitation of public input, over 150 options to help improve or maintain Basin resource reliability were received, many aimed at closing the supply and demand imbalance. The purpose of *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies* was to assess the effectiveness of those options at improving the reliability of the system to meet Basin resource needs.

8.1 Summary of *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*

8.1.1 System Reliability Analysis without Options and Strategies

The system reliability analysis without future actions or “Baseline” conditions, were modeled using CRSS, Reclamation’s long-term planning model, implemented in the RiverWare™ generalized river-reservoir modeling software. All combinations of the supply and demand scenarios were including the Baseline analysis. Additionally, two operational assumptions regarding Lake Powell and Lake Mead operations past the effective period of the 2007 Interim

Guidelines in 2026 were considered. Since each supply scenario has over 100 individual sequences, the Baseline system reliability is comprised of over 20,000 simulations or “traces”.

The Baseline simulations showed reduced streamflow at key locations and declining reservoir water elevations (pool elevation), as well as increasing risk of shortfalls in water availability to meet consumptive use demands. These conditions are further exacerbated when only considering the Downscaled GCM Projected water supply scenario. Although some of these findings translate directly to resource performance, many do not.

From the system reliability metrics (metrics) described in *Technical Report D – System Reliability Metrics*, a set of indicator metrics were developed to inform the assessment of vulnerability. Defining vulnerability required the definition of thesholds beyond which the resource was deemed vulnerable. This offered perspective on resource performance and also a quantifiable measure of outcomes. Consistent with the reductions in system reliability, resource-specific vulnerabilities were also found to increase as the supply and demand imbalance grows. Specific resource vulnerabilities resulting without options in place are discussed in the subsequent section, alongside the resulting vulnerability with options in place. The Baseline and each portfolio were evaluated for each combination of water supply and water demand scenarios and for operational assumptions.

8.1.2 System Reliability Analysis with Options and Strategies

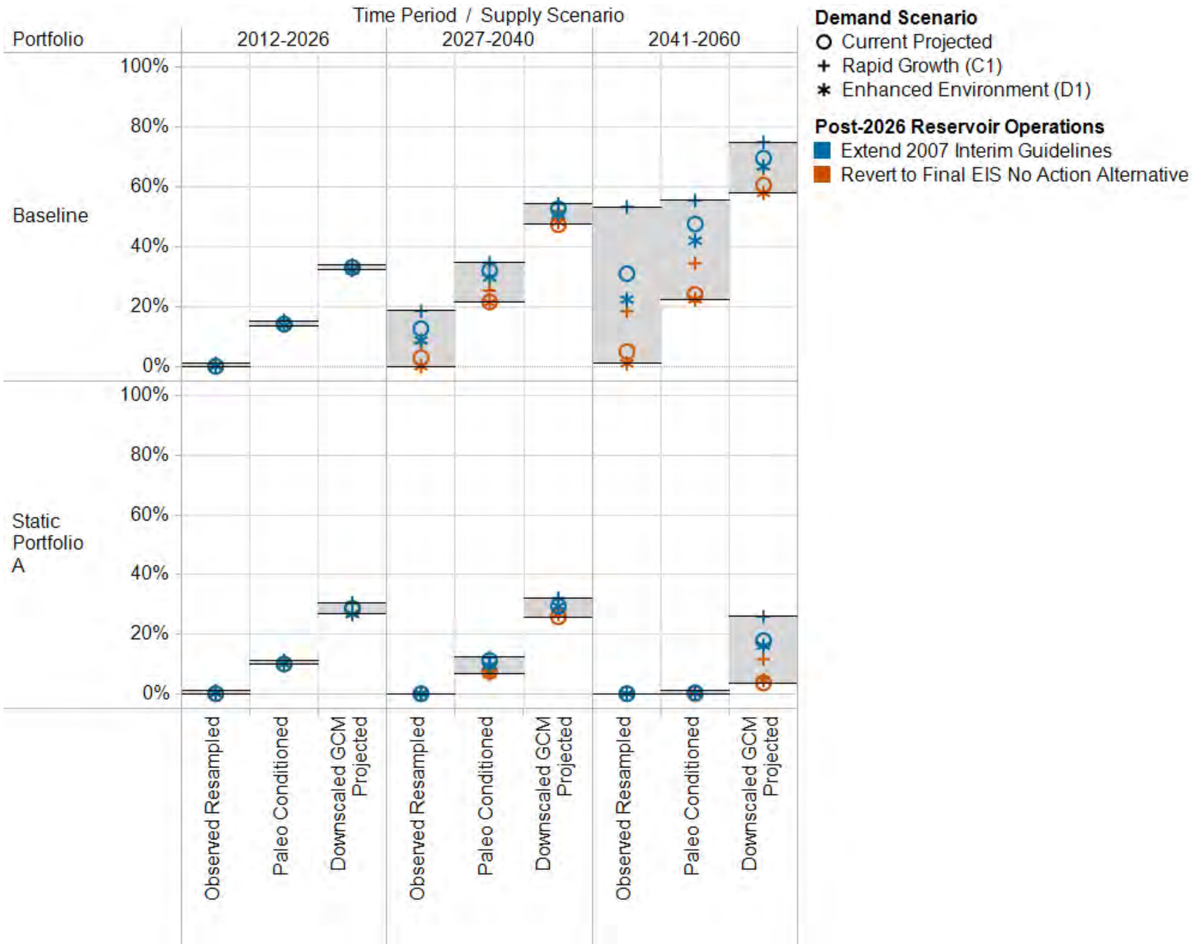
Static Portfolios

In addition to identifying a range of future demands, *Technical Report C – Water Demand Assessment* identified demands for Colorado River water beyond basic state apportionments in the Lower Division States. In the Baseline simulations, deliveries were limited to basic apportionments; as a result, these additional demands were only met during Surplus Conditions. Before attempting to address the added strain of demands growing beyond the Lower Division States’ basic apportionments, the effectiveness of options to remedy system performance within apportionment was explored. Due to the rather sizable supply and demand imbalances that are projected to occur, all representative options included in *Portfolio A*, described previously, were implemented as soon as available per their respective characterizations; such a strategy is referred to as *Static Portfolio A*. This ensures the full extent of the collective option capacity is considered in addressing vulnerabilities and imbalances. From this exercise, vulnerabilities were significantly reduced. In the case of some indicator metrics, the fraction of years vulnerable went from over 50 percent to as low as 5 percent. While this reduction was an encouraging indication of effectiveness, it is clear that in order to eliminate vulnerabilities entirely, additional investment would be required.

As established earlier, significant demands above basic apportionment exist and must be considered as part of a comprehensive study of the Basin and its resources. Several options generate potential yield that could be directed toward either these additional demands or toward broader Basin resources. Assumptions were developed that attempt to balance option benefits between these needs. In the implementation of *Static Portfolio A*, yield is directed to target demands above basic apportionments until system vulnerabilities increase measurably, upon which the benefit is directed away from meeting the demands and used to benefit Basin resources. This demonstrates the potential to strike a balanced approach with regard to yield benefit. Sensitivity results with different levels of balance between these needs show comparable improvements in resource vulnerability.

Using the *Static Portfolio A*, results for the Lake Mead pool elevation vulnerability, the impact of supply and demand scenarios on resource performance was explored by comparing against the Baseline results. Figure 18 shows two sets of model results – with and without options, delineated by time period, supply, demand, and assumption regarding Lakes Powell and Mead operations past 2026[22].

FIGURE 18
Percent of Vulnerable Traces for the Lake Mead Elevation Indicator Metric Across Three Time Periods for the Baseline and *Static Portfolio A*, by Supply and Demand Scenario



Graph reflects a subset of all scenarios evaluated for the portfolio analysis – Supply Scenarios: Observed Resampled, Paleo Conditioned, and Downscaled GCM Projected; Demand Scenarios: Current Projected (A), Rapid Growth (C1), Enhanced Environment (D1); Lakes Powell and Mead Post-2026 Operations: 2007 Interim Guidelines Extended, Revert to 2007 Interim Guidelines Final EIS No Action Alternative. Horizontal lines represent the minimum and maximum results across all demand scenarios.

22 For modeling purposes, future system conditions were modeled under two assumptions with respect to the operation of Lakes Powell and Mead beyond 2026. In one assumption, "Extend 2007 Interim Guidelines," it was assumed that the 2007 Interim Guidelines would remain in place from 2027 through 2060. In the other assumption, "Revert to Final EIS No Action Alternative," it was assumed that operations would revert back to those in the 2007 Interim Guidelines Final EIS No Action Alternative.

In the early time period (2012-2026), vulnerabilities are driven solely by supply scenarios; demand trajectories are still quite similar, and reservoir operations are governed by the 2007 Interim Guidelines. Even the difference between with and without options is somewhat small, mostly due to the lack of early options to address Lake Mead falling below 1,000 feet msl. The middle time period (2027-2040) shows some separation along the demand and operation policy dimensions, particularly for the Observed Resampled supply. However, for the more taxing hydrology scenarios, the differences in the percentage of vulnerable traces across demand scenarios become more muted. The effect of the portfolio has a similar dampening effect on the differences in the percentage of vulnerable traces across demand scenarios. In the final time period (2041-2060), differences due to demand and assumptions regarding Lakes Powell and Mead operations are at their largest, especially in the Baseline. The "Revert to No Action Alternative" assumption shows lower risk of vulnerability in Lake Mead elevation by creating sizable shortages in the Lower Basin. With the implementation of all options by the end of the final period, all but the Downscaled GCM hydrology vulnerabilities are reduced, again largely trumping the other parameters. Therefore, demand and operational policy can impact vulnerability outcomes but tend to be overshadowed by hydrology differences or portfolio implementation.

Dynamic Portfolios

To assess the appropriate timing of simulated option implementation, a dynamic method for implementing representative options was developed. In this method, options triggered only when needed, based on signposts that precede conditions associated with vulnerable events. These signposts are listed in table 12 and the use of them allowed for implementation of options in the model simulation only when needed. The lead time listed in table 12 was the longest period between the triggering of a signpost and occurrence of a vulnerability that still retained sufficient predictive skill. Additionally, only options that addressed the anticipated vulnerability were implemented given a particular signpost. However, signposts did not signal when feasibility-level studies, permitting, construction, or other key implementation decisions would be required. This would require a consistent and concerted effort to conduct project activities well in advance of triggers included in the model.

System Response Variables

Dynamic implementation of options in the model simulations of the four portfolios resulted in substantial system and resource improvements over Baseline results in addition to reducing over-investment. Relative to the static portfolio described above, the dynamic implementation of options reduces the annual portfolio cost by over 25 percent in 2060. This result speaks to the significant benefit to a dynamic and adaptive approach over one that is static.

In figure 19 and in all subsequent figures displaying portfolio results, in order to facilitate a comparison between the portfolios and Baseline conditions, the results were computed based on all supply and demand conditions and in addition for both assumptions regarding Lakes Powell and Mead operations after 2026.

Figure 19 shows all portfolios reversing the declining median Lake Powell pool elevations from the Baseline. Further, the 10th percentile pool elevation improved by 80 to 120 feet. It is noteworthy that even with such an improvement, levels can be still significantly low, indicating that some scenarios still pose a challenge to the system, even with options in place.

TABLE 12
Vulnerability Signposts

Indicator Metric/ Vulnerability	Lead Time	Conditions				
		Lake Powell Elevation (feet msl)	Lake Mead Elevation (feet msl)	Lees Ferry 5-year Mean Flow	Upper Basin Shortage	Lower Basin Demand Above Apportionment
Lee Ferry Deficit[1]	5 Years	3,490	Not applicable	12.39 maf	Not applicable	Not applicable
Lower Basin Shortage (>1 maf over 2 years)	3 Years	Not applicable	1,060’	13.51 maf	Not applicable	Not applicable
Lower Basin Shortage (>1.5 maf over 5 years)	3 Years	Not applicable	1,075’	13.51 maf	Not applicable	Not applicable
Mead Pool Elevation (< 1,000’)	3 Years	Not applicable	1,040’	13.35 maf	Not applicable	Not applicable
Upper Basin Shortage (>25%)	0 Years	Not applicable	Not applicable	Not applicable	25%	Not applicable
Lower Basin Demand Above Apportionment	Varies	Not applicable	Not applicable	Not applicable	Not applicable	Demand above basic apportionment is within 100 kaf of permissible level

[1] A Lee Ferry deficit is assumed to occur in any year when the 10-year running total flow at Lees Ferry is less than 75 maf. The deficit is computed as the difference between 75 maf and the 10-year running flow in a particular year.

Following results for Lake Powell are the probability and magnitudes of Lee Ferry deficits in figure 20. A Lee Ferry deficit is assumed to occur in any year when the 10-year running total flow at Lees Ferry is less than 75 maf. Again, all portfolios showed improvements over the increasing probability of Lee Ferry deficit seen in the Baseline. In some cases, the probability even appeared to have stabilized at less than 2 percent. Although the risk of a Lee Ferry deficit was notably lowered, the median magnitude was affected less. In fact, at the 90th percentile, there appeared to be some slight increases in deficit magnitudes. This is likely an artifact of reducing the number of deficit events, particularly those of smaller magnitudes, thus shifting some of the more-extreme condition to the 90th percentile. Importantly, the portfolios that stabilize the probability of a Lee Ferry deficit contain an option for an Upper Basin water bank. This bank is used to provide additional water to reduce the risk of Lee Ferry deficit.

FIGURE 19
10th, 50th, 90th Percentiles for Lake Powell End-of-December Pool Elevation for the Baseline and Four Portfolios

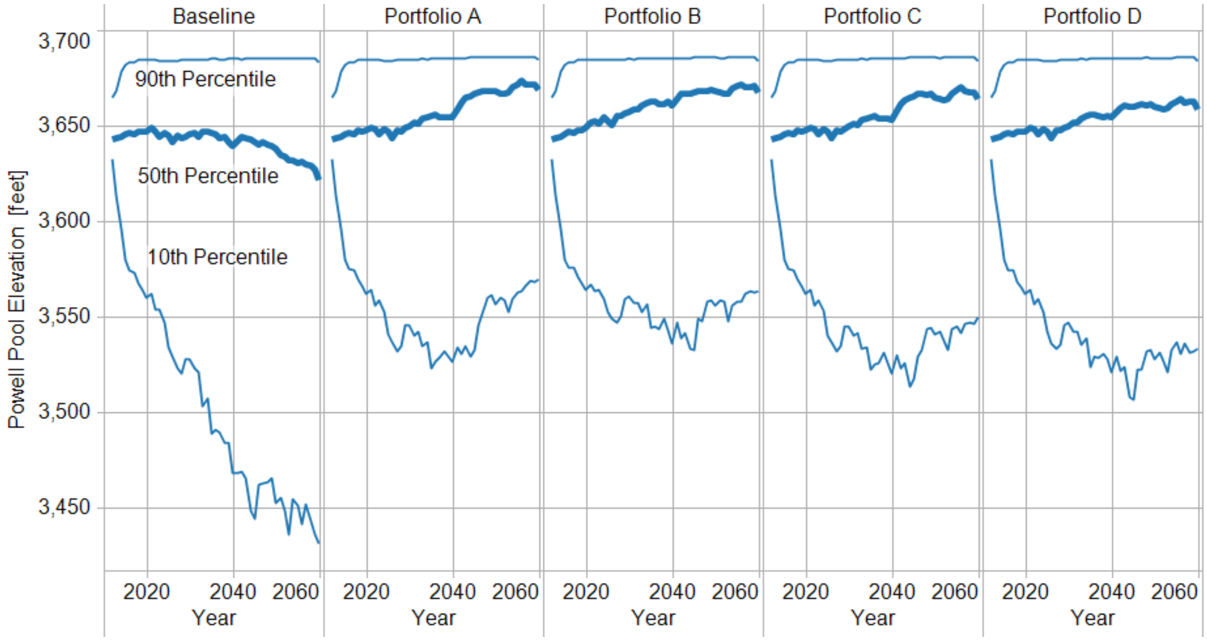
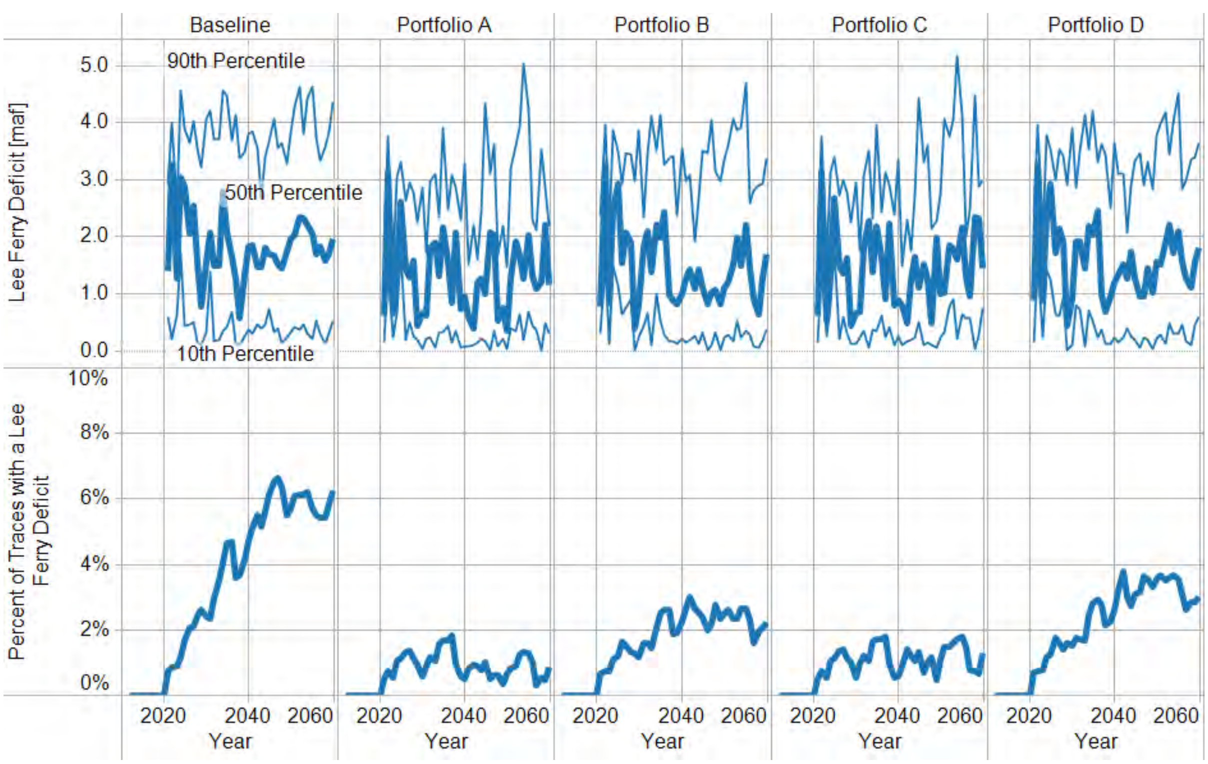
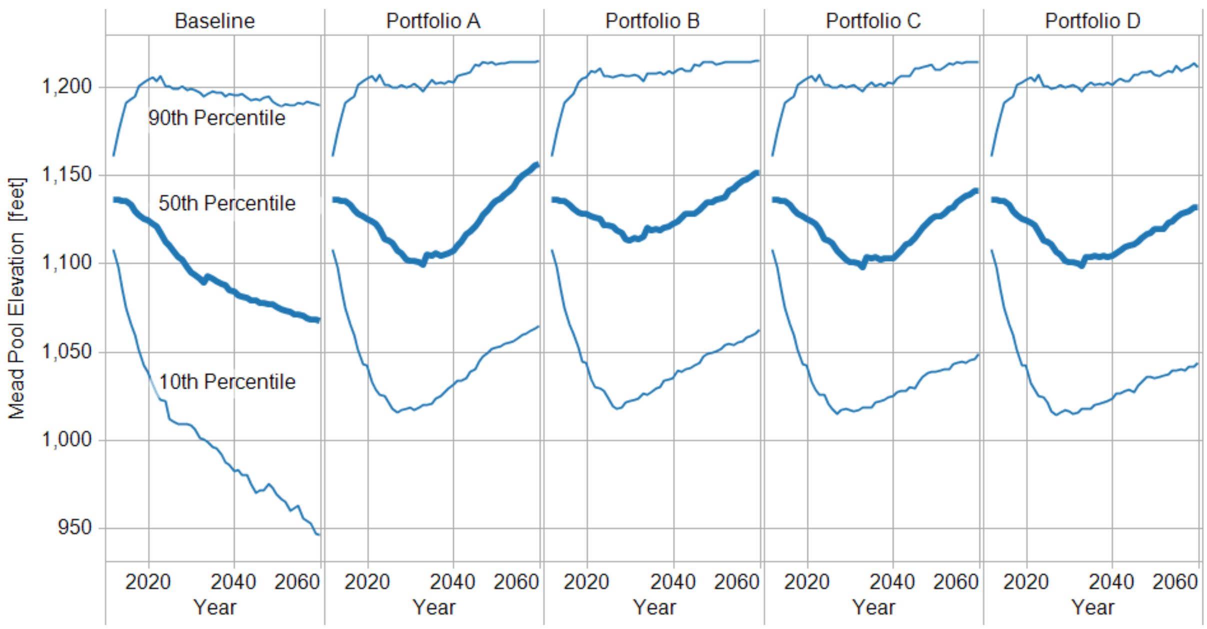


FIGURE 20
10th, 50th, 90th Percentiles for Lee Ferry Deficit in Years in Which a Deficit Occurs (top) and Percent of Traces (bottom) with a Lee Ferry Deficit for the Baseline and Four Portfolios



Lake Mead pool elevations also improved relative to the Baseline, albeit not as immediately and to a lesser magnitude, as shown in figure 21. The delayed recovery of the median pool elevation was due to a combination of option availability for implementation and the additional demands above basic apportionment that were not addressed in the Baseline run. These demands all originate in the Lower Basin, and therefore add extra demand strain on Lake Mead, calling for greater releases. In 2060, relative to the Baseline, median pool elevations rose 60 to 90 feet depending on the specific portfolio. Not surprisingly, *Portfolio A*, which had the largest maximum potential yield, saw the largest increase, whereas the *Portfolio D*, with smallest maximum potential yield, showed the smallest gains.

FIGURE 21
10th, 50th, 90th Percentiles for Lake Mead End-of-December Pool Elevation for the Baseline and Four Portfolios



Water Deliveries Indicator Metric Performance

Consistent with the improved system conditions, resource indicator metrics showed reductions in vulnerabilities. Figure 22 shows water delivery indicator metrics and percent of years vulnerable by three time periods. Additionally, in *Technical Report G – System Reliability Analysis and Evaluation of Options and Strategies*, results are shown for the percent of years vulnerable and indicating the percent of traces or simulated futures vulnerable. This helps in understanding the persistence of vulnerable events both within and across traces. For example, a low percent of years vulnerable but high percent of traces vulnerable, indicates that, albeit infrequently, the indicator metric tends to be vulnerable at least once in most traces. Conversely, a high percent of years but lower percent of traces vulnerable suggests considerable persistence of additional vulnerabilities once one has occurred for a particular trace.

FIGURE 22
Percent of Vulnerable Years for Each Water Delivery Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

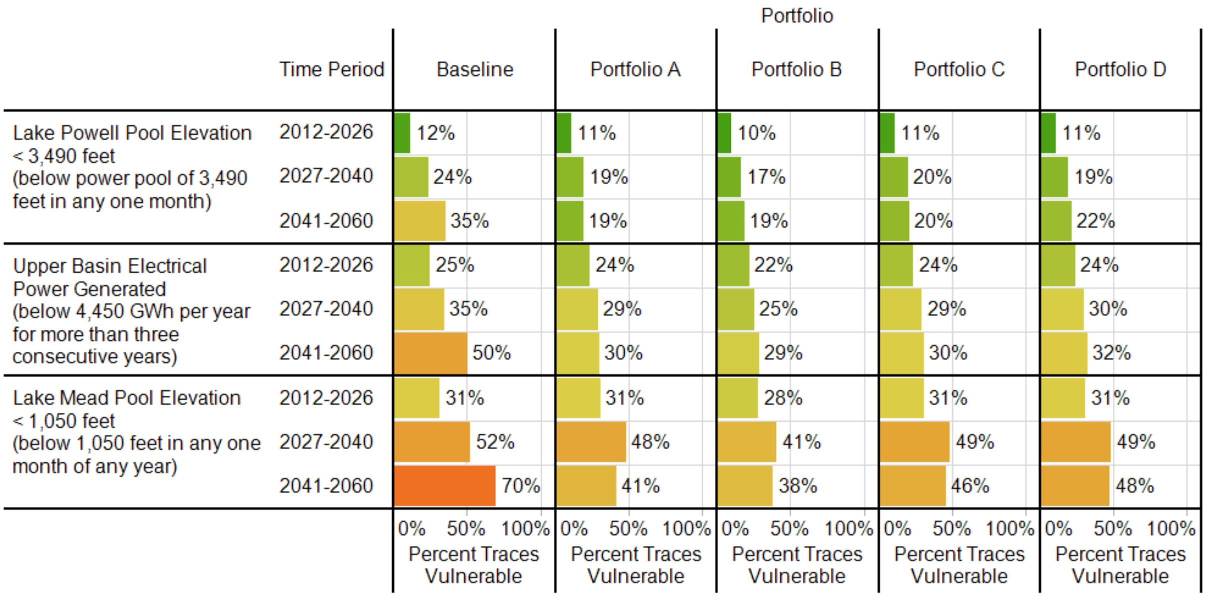
	Time Period	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Upper Basin Shortage (exceeds 25% of requested depletion in any one year)	2012-2026	4%	3%	3%	3%	3%
	2027-2040	5%	3%	3%	3%	3%
	2041-2060	7%	2%	2%	3%	3%
Lee Ferry Deficit (exceeds zero in any one year)	2012-2026	0%	0%	0%	0%	0%
	2027-2040	3%	1%	2%	1%	2%
	2041-2060	6%	1%	2%	1%	3%
Lake Mead Pool Elevation < 1000 feet (below 1000 feet in any one month)	2012-2026	4%	4%	4%	4%	4%
	2027-2040	13%	7%	7%	8%	8%
	2041-2060	19%	3%	3%	5%	6%
Lower Basin Shortage (exceeds 1 maf over any two year window)	2012-2026	7%	5%	5%	5%	5%
	2027-2040	37%	22%	19%	23%	23%
	2041-2060	51%	10%	10%	13%	14%
Lower Basin Shortage (exceeds 1.5 maf over any five year window)	2012-2026	10%	9%	9%	9%	9%
	2027-2040	43%	35%	30%	36%	36%
	2041-2060	59%	23%	23%	26%	28%
Remaining Demand Above Lower Division States' Basic Apportionment (exceeds moving threshold in any one year)	2012-2026	0%	0%	0%	0%	0%
	2027-2040	40%	2%	1%	1%	2%
	2041-2060	93%	5%	5%	7%	5%
		0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable

For all metrics shown, vulnerabilities in the first period tended to change little from the Baseline results. This was a result of the combination of often low vulnerability risk in the early period and few options available to address vulnerabilities when they occur. The middle time period was the first to significantly diverge from the Baseline for most indicator metrics. However, in some cases, it was also the most vulnerable window, owing to the fact that options may have only been available for a short time, and as a result, little benefit accrued to reduce vulnerability. Demands above basic apportionments were not included in the Baseline modeling and thus the results showed a marked improvement under simulations with portfolios. Also, one might expect *Portfolio A* to show the greatest reduction in vulnerabilities simply by having the greatest yield available to address imbalances; however, this was not always the case. Because this portfolio includes the Upper Basin banking option, water generated by conservation was not immediately available to address vulnerabilities, but was instead "banked" to help hedge against future Lee Ferry deficits. This is the same reason that *Portfolio A* was particularly effective at reducing the probability of Lee Ferry deficits.

Electrical Power Resources Indicator Metric Performance

As shown in figure 23, electric power resources exhibited performance improvements similar to those in the water delivery indicator metrics. As more options are implemented, increased flow helps to raise pool elevations and greater downstream demand requires larger releases. This combination is a two-fold benefit to hydropower.

FIGURE 23
Percent of Vulnerable Years for Each Electric Power Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

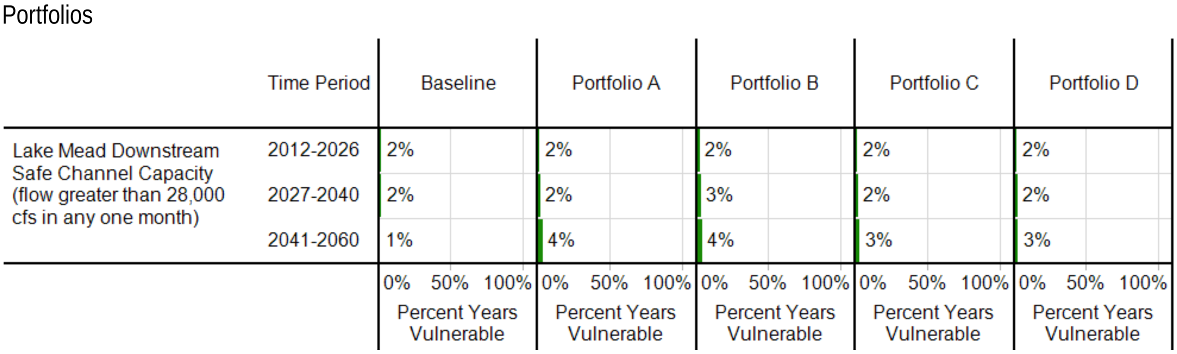


Gigawatt hour (GWh)

Flood Control Indicator Metric Performance

As shown in figure 24, under the Baseline conditions, flood control vulnerabilities were few and actually decreased over time due to the increase in available storage associated with increasing demand. Under the various portfolios, the occurrence of vulnerabilites remained low, but did increase slightly. This result stems from the implementation of options that increase pool elevations, which in turn, reduces capacity to absorb extreme flow events.

FIGURE 24
Percent of Vulnerable Years for Each Flood Control Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios



Cubic feet per second (cfs)

Recreational Resources Indicator Metric Performance

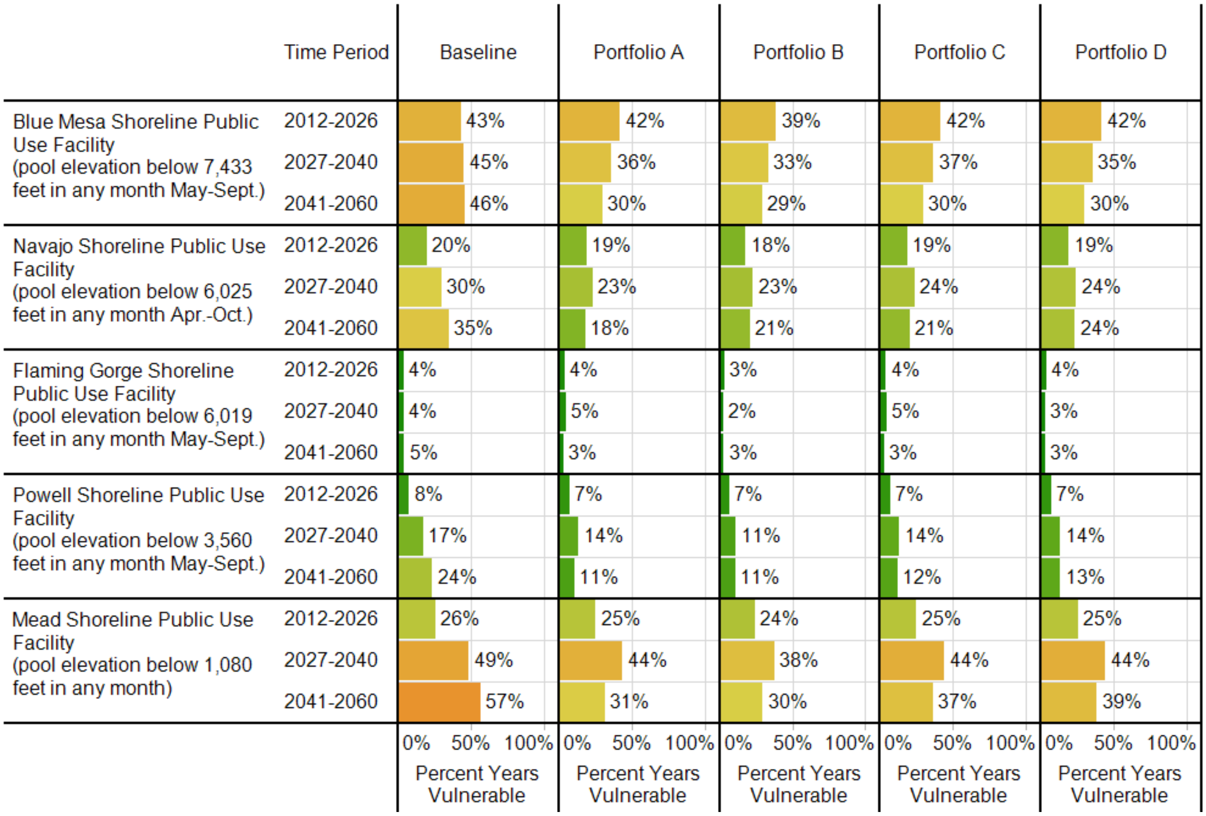
Figures 25 and 26 show recreational resource indicator metric vulnerabilities. Specifically, the metrics in figure 25 are river boating vulnerabilities, and those in figure 26 pertain to reservoir recreation. River boating indicator metrics are based on the shift in long-term average availability of flows deemed acceptable (total days) and optimal (optimal days) from simulations reflective of current conditions with variable hydrology (control run). In general, the optimal flow metrics were consistently more vulnerable than the total flow metrics. This is because the window for optimal flows is more stringent and therefore more sensitive to changes in streamflow. All portfolios demonstrate improvements for the boating indicator metrics. *Portfolio A* showed the most improvement. The improvement in *Portfolio A* and in *Portfolio C* is due to the Upper Basin banking option, found in both, which routes conserved water from across the major tributaries to a conceptual storage facility near Lake Powell. By routing the conserved water, resources that depend on in-stream flows tend to benefit, including river boating recreation.

FIGURE 25
Percent of Vulnerable Years for Each Recreational (boating flow) Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

	Time Period	Baseline	Portfolio A	Portfolio B	Portfolio C	Portfolio D
Colorado River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	10%	9%	9%	8%	9%
	2027-2040	31%	24%	26%	24%	28%
	2041-2060	38%	25%	28%	28%	32%
Green River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	7%	6%	6%	6%	7%
	2027-2040	21%	15%	17%	16%	19%
	2041-2060	25%	16%	19%	16%	20%
San Juan River Optimal Boating Flow Days (below 10th percentile of control run)	2012-2026	5%	4%	5%	4%	5%
	2027-2040	19%	10%	16%	11%	18%
	2041-2060	27%	15%	22%	16%	23%
Colorado River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	6%	5%	4%	5%	5%
	2027-2040	21%	14%	14%	14%	17%
	2041-2060	30%	14%	16%	17%	19%
Green River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	1%	1%	1%	1%	1%
	2027-2040	5%	1%	4%	2%	4%
	2041-2060	8%	2%	4%	2%	5%
San Juan River Acceptable Boating Flow Days (below minimum of control run)	2012-2026	2%	2%	2%	2%	2%
	2027-2040	7%	2%	5%	2%	6%
	2041-2060	13%	3%	7%	4%	9%
		0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable	0% 50% 100% Percent Years Vulnerable

"Control run" reflects conditions that might be expected under current demand and Observed Resampled water supply conditions, and was used as a reference for evaluating change in vulnerability associated with future changes.

FIGURE 26
Percent of Vulnerable Years for Each Recreational (shoreline facilities) Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios

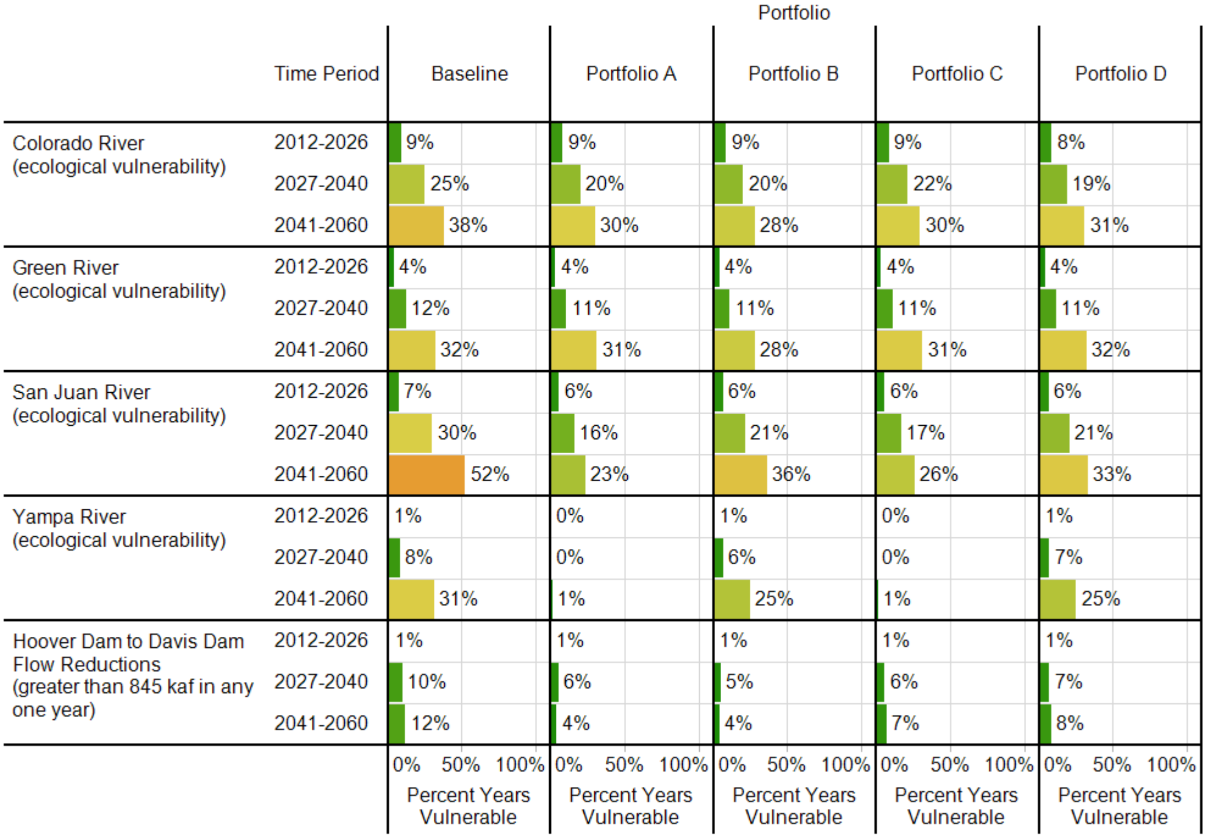


For reservoir recreation, Flaming Gorge performed notably well, even under the Baseline simulations. This is attributable to a combination of more-optimistic streamflow projections in the Upper Green River due to projected climate change and slower growth relative to other regions. Reductions to vulnerabilities at other locations in the Upper Basin were largely from conservation and weather modification options that serve to either increase reservoir inflow or reduce the required release.

Ecological Resources Indicator Metric Performance

Ecological resource vulnerabilities were calculated based on reference flow conditions that were derived to reflect instream and riparian habitat conditions. In most cases, the indicator metrics were derived from biological opinion recommendations and coordinated through the Metrics Sub-Team. Ecological resource indicator metrics are shown in figure 27. Based on the discussion of river boating vulnerabilities, it would be logical to expect that the portfolios with the Upper Basin banking option and associated routing of flows would benefit ecological resources more than other portfolios. In the case of the Yampa and San Juan river metrics, the outcome was consistent with this expectation. However, for the Green and Colorado rivers, the improvements were largely commensurate with other portfolios because of the particular flow recommendations at those sites. The Green and Colorado river flow prescriptions are specific with regard to timing and volume. As such, increases in flow resulting from routing water to the bank may not help resolve vulnerabilities if the flow pattern is not consistent with the flow recommendations. Coordinated routing of flows would be required to achieve the maximum benefit to those more-detailed flow requirements.

FIGURE 27
Percent of Vulnerable Years for Each Ecological Indicator Metric Across Three Time Periods for the Baseline and Four Portfolios



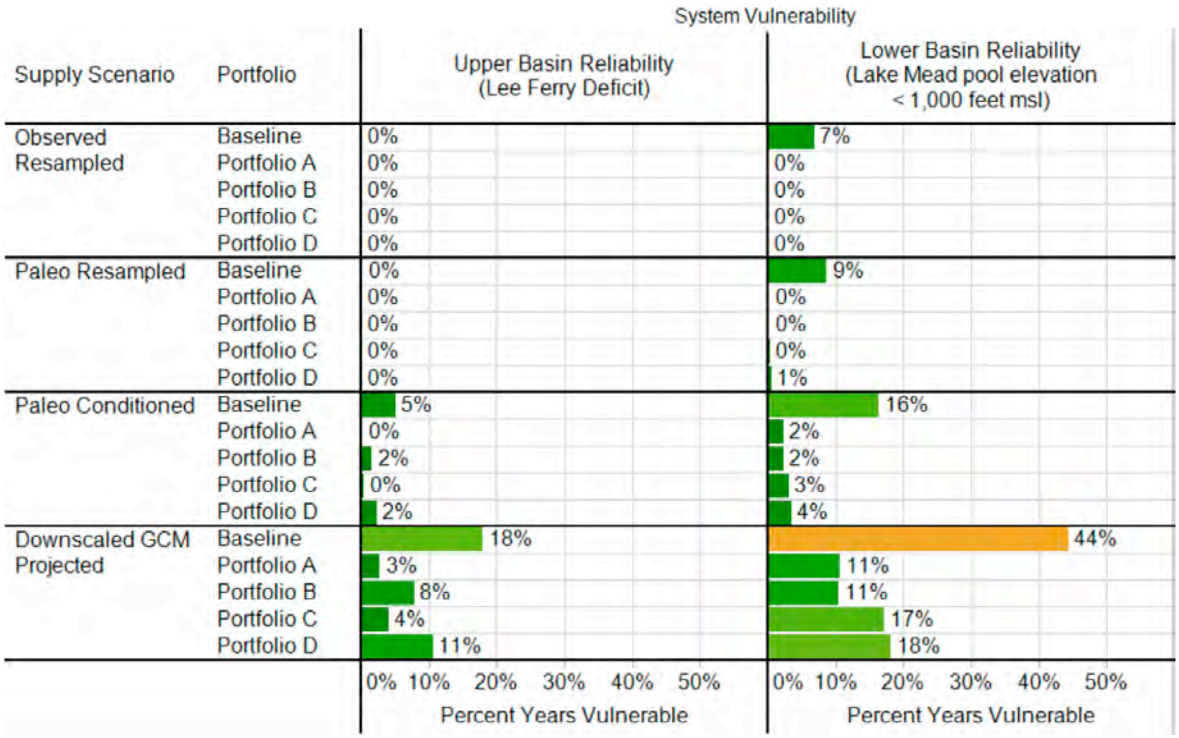
8.1.3 Portfolio Comparison and Option Analysis

Although the portfolio analysis successfully demonstrated that system reliability can be improved, it is not without significant cost and performance tradeoffs. Figure 28 illustrates the performance across portfolios by supply scenario in terms of addressing two key water delivery vulnerabilities—Lee Ferry deficit and Lake Mead pool elevation below 1,000 feet msl. For this discussion these are refered to as the Upper Basin vulnerability and Lower Basin vulnerability.

Portfolio B favors options believed to have higher certainty of available water supply once implemented. As shown in figure 28 (on the right), this portfolio performs as well or better than all the other portfolios for addressing the Lower Basin vulnerability across all supply scenarios. The portfolio performs less well than *Portfolios C* and *A* for the Upper Basin vulnerability (figure 28, left), 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 conservation and reuse. Choosing to implement options characterized as having low energy needs (as a surrogate for potential environmental impacts) might come at the expense of having a less certain long-term water supply. Despite this tradeoff, this portfolio performs well for addressing the Upper Basin vulnerability (figure 28, left) and is particularly effective under the Downscaled GCM Projected supply scenario (figure 3, bottom row). *Portfolio C* is less effective, however, at addressing the Lower Basin vulnerabilities (figure 28, right). Note that the effectiveness of *Portfolio C* and *Portfolio A* at reducing Upper Basin shortage vulnerability is largely due to the inclusion of a Upper Basin water bank concept in these portfolios.

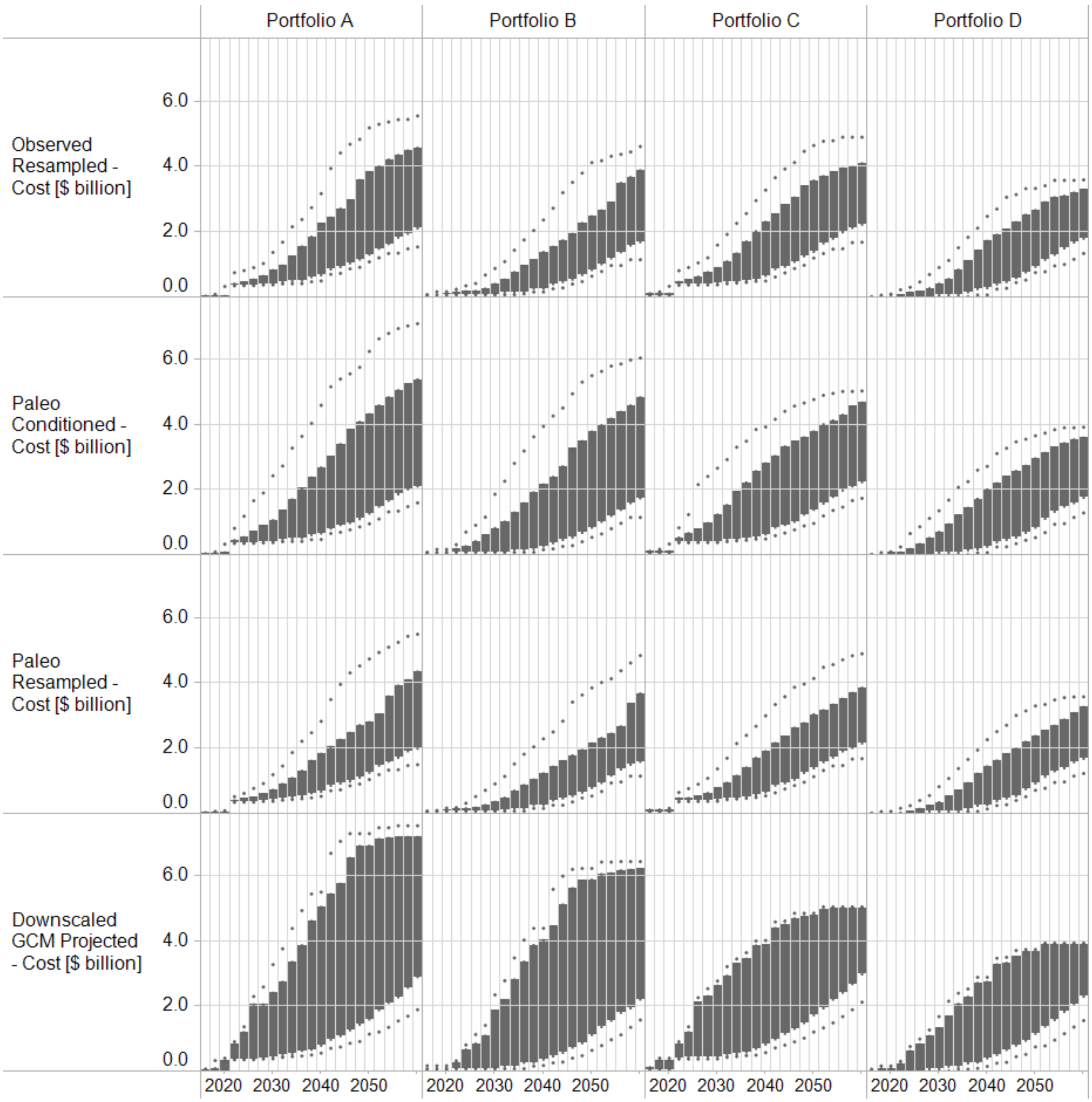
FIGURE 28
Percent of Years with Occurrence of Upper Basin (left) and Lower Basin (right) Vulnerability in 2041–2060 with Portfolios Implemented, by Supply Scenario



As discussed earlier, portfolios differ based on the representative options available to address supply and demand imbalances. As such, it is important to explore the portfolios beyond their ability to reduce vulnerabilities and improve system conditions. From analysis of the characterization criteria, the portfolios considered in the Study differ most notably on cost, energy needs, and long-term viability factors. Figure 29 shows the distribution of annual portfolio costs through time and for each water supply scenario. The box plots in the figure represent the inter-quartile range and the 10th and 90th percentiles. For all portfolios, costs increase substantially between the onset and end of the Study period. By 2060, the annual costs range from approximately \$2 to \$5 billion under the Observed Resampled, Paleo Conditioned, and Paleo Resampled supply scenarios, and increase to potentially \$7 billion under the Downscaled GCM Projected scenario. *Portfolio A* is the most costly due to the inclusion of the greatest number of options, and *Portfolio D* is the least costly due to the inclusion of the least number of options. Although *Portfolio B are* costly, it brings a certainty of available supply and is risk averse in terms of the future security of providing water to users. By choosing to only consider options that were characterized as having moderate to high long-term viability, lower unit cost alternatives were excluded, which also had the effect of lowering total potential yield.

Portfolio C is similar in cost range to *Portfolio B,* except under the GCM Projected scenario, where it is less expensive largely due to the exclusion of some options that are only triggered under more-challenging water supply conditions within *Portfolios A* and *B.* Within *Portfolio C*, the emphasis on options characterized as having low energy needs might come at the expense of yield certainty. The purpose of exploring these differences is not to identify a "best" portfolio or strategy, but to acknowledge that there are various ways to address the supply and demand imbalance and that each has associated implications that must be considered in future planning and decision-making processes.

FIGURE 29
Total Annual Cost by Supply Scenario Resulting from Implementation of the Portfolios over Time



The spread between the 25th and 75th percentile is indicated by shading. The 10th and 90th percentile values are indicated by the x's.

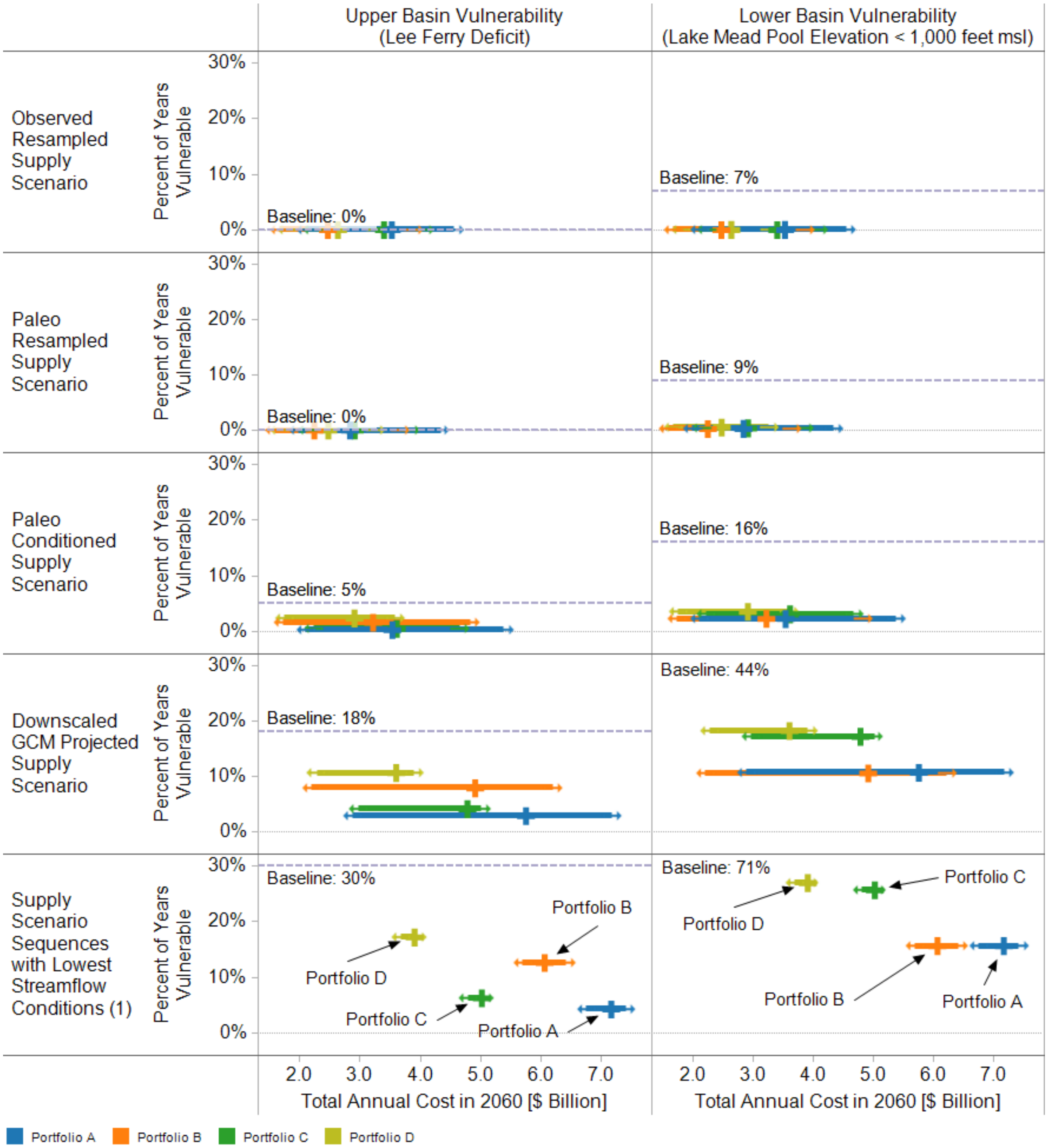
The intersections of cost, characteristics, and performance bound the discussion of portfolios and highlight the strategies used to craft each. Tradeoffs also exist with respect to portfolio costs, and these differ depending on the specific future conditions.As shown in figure 30, the annual cost, in 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 inter-quartile ranges of cost are significantly larger. However, because of the appraisal-level option cost estimating used in the Study, the cost values contain additional uncertainty not directly reflected in these estimates.

When considering how the portfolios perform in stressing hydrologic conditions often associated with critical water delivery reliability vulnerabilities, the differences among the portfolios in terms of costs and ability to reduce vulnerability are more apparent. As conditions become less favorable, such as in the “Lowest Streamflow” subset of sequences (figure 30, bottom row), *Portfolios C* and *A* perform the best with respect to the Upper Basin Vulnerability and *Portfolios B* and *A* perform the best with respect to Lower Basin Vulnerabiltiy.

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 costs less than *Portfolio A*.

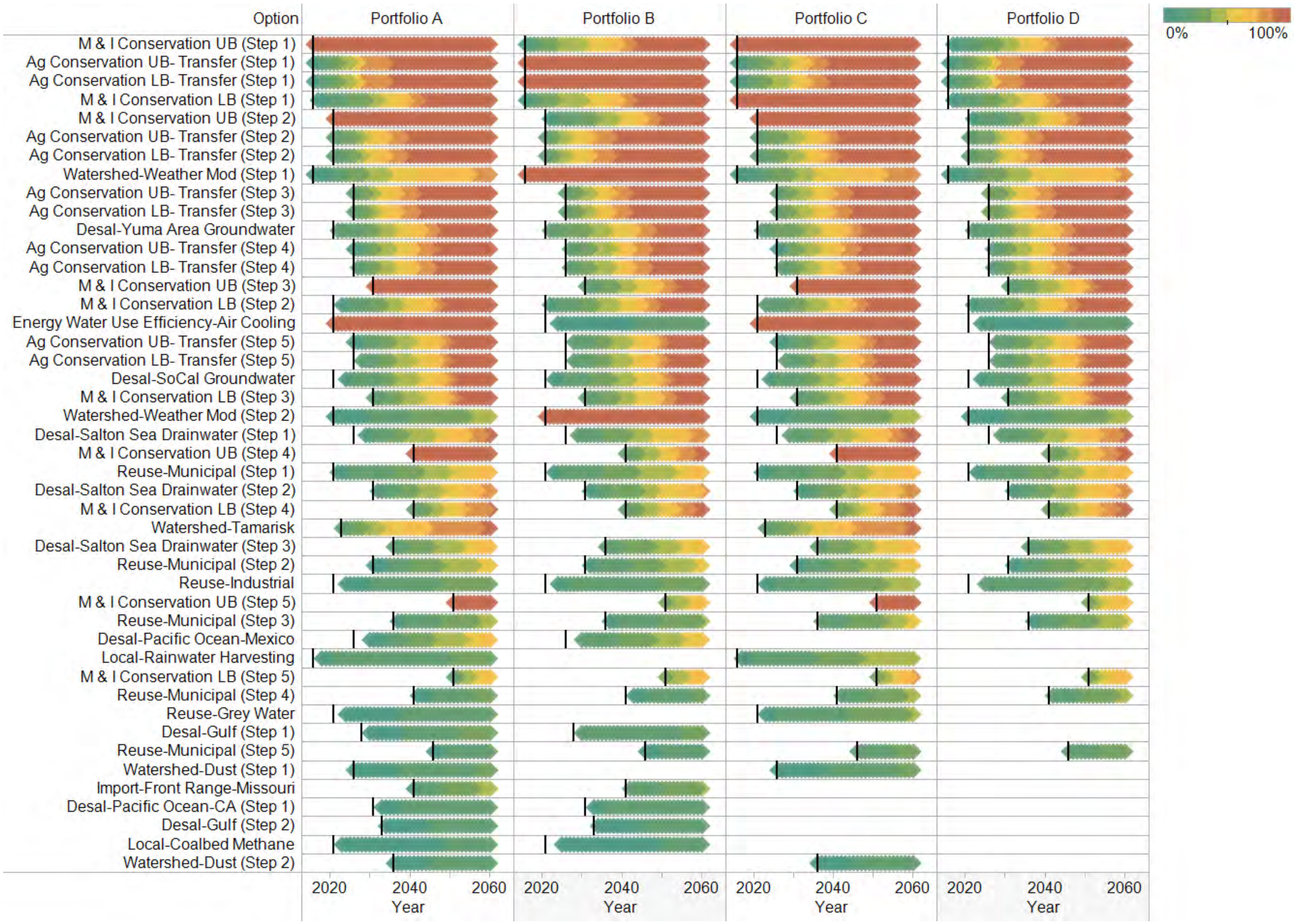
Portfolios were also evaluated for which options were implemented for each dynamic portfolio. Figure 31 shows the implementation frequency through time for options in each portfolio. Many options are common among all portfolios, but the frequency of use informs how each portfolio resolves the imbalance in a slightly different manner. The small vertical black line indicates the earliest possible date that the option could be available, assuming project feasibility is initiated today. Options that are implemented with high frequency shortly after becoming available suggest that investigation in the near future may be prudent due to the simulated short delay between availability and selection. In the case of *Portfolio A* and *Portfolio C*, conservation is implemented as soon as available in order to generate water for the Upper Basin bank. These are not triggered by signposts, but rather are assumed to be in place ahead of time to make this preventive strategy effective. In a broad sense, options such as agricultural conservation and transfers and M&I conservation are considerably relied upon in each portfolio because they are available early to address many vulnerabilities. However, as conditions become more challenging and the imbalance widens, there is also need for other options, such as desalination, reuse, and importation that may only be available in the longer term.

FIGURE 30
Portfolio Cost and Percent of Upper Basin (left) and Lower Basin (right) Vulnerability for 2041–2060, by Supply Scenarios and Lowest Sequences



(1) Conditions in which long-term mean natural flows are less than 14 mafy and the 8-year dry period flows are less than 11 mafy.
(2) Marker indicates the 50th percentile result and the bounds represent 25th and 75th percentile results.

FIGURE 31
Frequency of Option Implementation (percent of traces) for Each Portfolio



Through evaluation of the option implementation results across and within portfolios, the following findings can be summarized:

- Options that were frequently implemented and with a short delay from their first availability date: M&I Water Water Conservation (for all portfolios); Agricultural Water Conservation and Weather Modification (for *Portfolio B*); Energy Water Use Efficiency (for *Portfolios A* and *B*). Implementation of these options was common across portfolios and may require advanced planning as illustrated by the short delay in model implementation.
- Options that were frequently implemented and with a short delay under the Low Streamflow conditions (long-term flow less than 15 mafy and drought less than 13 mafy): Salton Sea Drainwater Desalination; Agricultural Water Conservation (all portfolios); Municipal Wastewater Reuse (*Portfolio C and D*). Implementation of these options was common across portfolios with short delay under low streamflow conditions. These options may also need advanced planning in order to hedge against these challenging conditions.
- Options that were frequently implemented and with short delay under the lowest streamflow conditions (long-term flow less than 14 mafy and drought less than 11 mafy): Desalination of Brackish Water in the Yuma Area; Missouri River Imports (*Portfolios A and B*). These options may only require advanced planning to hedge against the more severe conditions.
- Options that were frequently implemented, but with a longer delay under the Low Streamflow conditions (long-term flow less than 15 mafy and drought less than 13 mafy) include: Gulf of California Ocean Desalination, Pacific Ocean Desalination in California, Grey Water Reuse, and Dust Control, and Treatment of Local-Coal Bed Methane Produced Water. These options may allow for some delay in implementation.

8.2 Summary of the Evaluation of Options and Strategies

The system reliability analysis with options and strategies demonstrated that all portfolios have capacity to reduce vulnerabilities across resources and in doing so, making a sizeable reduction in the supply-demand imbalance. In the 2012 through 2026 period, reductions in vulnerabilities tend to be small, owing to generally low risks and lesser option availability in the near-term. In the latter two time windows, vulnerability reductions of 50 percent or more (relative to Baseline results) are seen in all resource categories. The one exception is the flood control indicator metric. A consequence of increased Basin yield and greater storage in reservoirs is a slight increase in flood control vulnerabilities.

The four portfolios explored in the Study were shown to significantly reduce Upper and Lower Basin vulnerabilities, but implemented different strategies. Of the four strategies and associated portfolios considered, notable differences extend beyond portfolio performance. Portfolio cost is driven by the total potential yield considered in the portfolio, the unit cost of the options, and the water supply and water demand conditions for which the portfolio was evaluated. As such, by 2060, annual portfolio costs range from approximately $2 billion to $5 billion, but could increase to potentially $7 billion under the Downscaled GCM Projected scenario. The differences in cost across portfolios result from the preference of option types versus increased ability to reduce vulnerabilities. Two examples of this are portfolio preferences for options with higher long-term reliability and preferences for lower environmental impacts. By choosing to only consider options that were characterized as moderate to high long-term viability, lower unit cost alternatives may be excluded, but the options increased the total potential yield. In contrast, options characterized as having lower potential environmental impacts may come at the expense of yield certainty. The purpose of exploring these differences is not to identify a "best" portfolio or strategy, but to acknowledge that there are various approaches to address the future supply and demand imbalance and that each has associated implications that must be considered in the decision making process.

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.

9.0 Study Limitations

As stated previously, the focal questions being addressed by the Study were:

- What is the future reliability of the Colorado River system to meet the needs of Basin resources through 2060?
- What are the options and strategies to mitigate future risks to these resources?

Although the technical approach of the Study was based on the best science and information available, as with all studies, there are 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, methods, and the capability of existing models. Many of these limitations could not be overcome for purposes of the Study because of time and resource constraints. In some cases, these limitations presented opportunities for additional research and development and the improvement of available data. These opportunities will be pursued in efforts independent of the Study. Limitations exist in the areas noted below.

9.1 Treatment of Lower Basin Tributaries

For four of the inflow points below Lees Ferry (the Paria, Little Colorado, Virgin, and Bill Williams rivers), CRSS uses historical inflows (not natural flows) based on USGS streamflow records. In addition, the Gila River is not included in CRSS.

Many Colorado River planning studies have been completed over the past two decades where this treatment of the major Lower Basin tributaries was used; however, questions regarding the adequacy of the treatment of the Lower Basin tributaries in CRSS for the Study arose during the phases focused on assessing future water supply and demand. 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 CU&L Reports limited the ability of the Study to gain a more-complete understanding of historical consumptive use in the Basin.

Despite these limitations, other approaches were taken in the Study to examine several important issues, including potential climate change impacts on the tributaries represented in CRSS, future demand scenarios on those tributaries, and future demand scenarios for the Colorado River from the Gila River Basin, factoring in other water supplies within that basin.

Reclamation will engage in efforts to: (1) resolve and correct, in collaboration with the Basin States, the methodological and data inconsistencies in the CU&L Reports pertaining to all of the Lower Basin tributaries; (2) develop natural flows for the Little Colorado, Virgin and Bill Williams rivers and modify CRSS to use natural flows for those tributaries; and (3) explore the feasibility and usefulness of computing natural flows for the Gila River Basin and the feasibility and usefulness of adding that basin to CRSS. Refer to *Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System* for a more-detailed discussion of these issues.

9.2 Treatment of Agricultural Land Use in Water Demand Scenarios

The water demand storylines were developed by the Water Demand Sub-Team which included participation from a broad range of stakeholders. The sub-team developed storylines based on key driving forces that represented a range of plausible futures regarding future demand. However, the assumptions in some storylines with regard to these 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. Given recent projections of increased agricultural productivity necessary to meet future food needs, plausible futures should include increases in land use.

The application of a scenario planning approach to project future Basin-wide demand represents a new paradigm in the Basin and a significant advancement in Basin long-term planning. Reclamation and the Basin States are committed to continued refinement of scenario planning as part of a robust long-term planning framework for the Basin.

9.3 Ability to Assess Impacts to Basin Resources

The ability to assess impacts to Basin resources was limited by the spatial and temporal detail of CRSS. Described further in *Technical Report D – System Reliability Metrics*, some metrics have limitations in their ability to be assessed quantitatively and in some cases were assessed qualitatively. For example, CRSS tracks shortages in the Upper Basin when the flow is insufficient to meet the local demands as opposed to simulating the complex water rights system in each state that would be needed to appropriately model shortages to individual water rights holders and the lack of model representation of individual tributaries. This representation affected the ability of the Study to assess the impacts to deliveries in the Upper Basin. Another example is that several ecological resources metrics were evaluated through approximations at larger spatial scales and longer timesteps (e.g., monthly versus daily) than preferred or required for more-detailed assessments.

In some cases, particular modeling assumptions limited the detailed analysis of certain metrics. For example, when water is supplied to the system in the manner assumed to determine the Lee Ferry defecit, the uncertainty regarding metric results increases, particularly in the Upper Basin. However, due to the infrequent occurrence of a Lee Ferry deficit across all traces, these results are not disregarded. This uncertainty, however, should be considered carefully when viewing metric results, particularly in the Upper Basin, that have been impacted by this modeling assumption.

9.4 Options Characterization Process

The process undertaken to characterize options to help resolve potential water supply and demand imbalances strived to maintain an objective and consistent evaluation of the options. Several iterations of the option characterization were performed in an attempt to normalize ratings wherever possible. However, several limitations were inherently associated with the characterization of the over 150 options received. The limitations identified during the characterization process include the following:

- ***Limited Level of Analysis.*** The intent of the characterization was to perform a high-level analysis of a broad range of options potentially available to resolve Basin imbalances. This high-level analysis added the risk that not all of the potential costs and benefits of the options were considered. A detailed assessment by individual location for most of the distributed options (e.g., M&I water conservation, agricultural water conservation, and reuse) was beyond the scope of the Study.
- ***Potential for Subjectivity.*** The classification system used in the characterization process was relatively prescriptive; however, there was still some room for subjectivity when considering each option. Not all participants in the Study were in agreement with all ratings, but it was recognized that future efforts beyond the Study will result in a more in-depth assessment of the options.
- ***Uncertainty.*** The characterization was performed based on limited and high-level analyses. Therefore, knowledge of items such as costs, permit requirements, and long-term feasibility was highly uncertain. For example, cost estimates for infrastructure-type projects were based on past similar projects with adjustments for parameters such as scale and location. Similar statements can be made related to uncertainty with characterization of the other option criteria.

9.5 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.

10.0 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, particularly those areas where demand is at or exceeds available supply, are at a 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 is ultimately a call to action. The potential improvements in system performance and enhanced resiliency resulting from the portfolio analysis is encouraging, however a very long lead time is required to implement many of the portfolio options. When considering the potential onset of critical imbalances as early as 2025, it is imperative that the processes to further these concepts must begin in the near future. The next steps to begin these actions must be done collaboratively and continue to facilitate and build upon the broad, inclusive stakeholder process demonstrated in the Study.

The call to action must be answered by all stakeholders that rely on the Colorado River or its tributaries. Given the uncertainty associated with future conditions in the Basin, the ability to increase water supply reliability is even more important. There is no one option or one path that will provide certainty for the future water supply and rivers of the Basin. Responding to the uncertainty will require understanding all potential options and taking action must be the responsibility of all stakeholders. The political will to take necessary action must be directed towards a credible process to create solutions which examines the trade-offs of using various options while seeking to meet a range of Basin resource goals. As the next steps are taken, all stakeholders must be involved in considering future options and strategies and all evaluation and analysis of these options must be done with a high level of transparency with independent scientific review and opportunities for public comment.

The following sections describe those areas where additional steps should be taken following completion of the Study. These areas and recommended future actions are presented thematically and were developed cooperatively by Reclamation, the Basin States, tribes, and various conservation organizations.

Water Use Efficiency and Reuse

Further efforts to improve water use efficiency in the M&I, agricultural and energy sectors were a common element across all Study portfolios in providing a cost-effective solution for resolving imbalances in the near-term. This is an area that municipalities and entities in the agricultural sector have been and will continue to pursue. The approach taken by the Study to determine the potential for conservation in these sectors and their respective costs was at a Basin-wide level. Although appropriate for the Study, this approach does not reflect the important local differences in conservation potential nor does it reflect the legal issues associated with the various state water right policies. A key issue to be explored is the significant uncertainty related to the potential magnitude of conservation included in the Study.

A recommended next step is to establish workgroups associated with municipal conservation, agricultural conservation, energy conservation, and reuse. These workgroups would be convened by Reclamation. The purpose of the workgroups would be to identify existing programs, projects, and policies applied to municipal, agricultural, reuse, and energy sector conservation and the distribution of those programs across water users throughout the Study Area. The goal of these workgroups would be to consider new opportunities and programs, and potentially to develop a scope of work for feasibility-level studies to develop new approaches to encourage conservation that address key uncertainties and financial impacts. The groups' objectives will include focusing on water use efficiency at a local level, the application of approaches appropriate for different locations and regions, and exploring innovative and cost-effective ways to encourage increased water use efficiency and reuse opportunities with the goal of recommending the implementation of solutions resulting in cost-effective water savings and reuse.

Reclamation’s WaterSMART program provides several opportunities that could be used to further study and implement water conservation and reuse options. Through WaterSMART grants, funding could be made available for projects that save water or improve energy efficiency. The criteria for administering these grants could be modified to give preference to activities that build upon Basin Study outcomes. Through the WaterSMART Title XVI – Water Reclamation and Reuse Program funding could be made available for planning studies and the construction of water recycling projects.

Water Banks

Water banks are a flexible and innovative solution to avoiding imbalances. Both intrastate and interstate water banking occurs within the Lower Basin. In the Study, a conceptual Upper Basin water bank was explored where the benefit was twofold: 1) the bank provided increased flexibility in the Upper Basin to mitigate risk of potential future Lee Ferry deficits and 2) the water generated through conservation for the bank enhanced ecological and recreational resources as it was routed to a conceptual storage facility. Although there are significant legal, policy, and institutional challenges associated with potential banking options, the potential benefits associated with this option suggest that additional exploration and analysis of this concept may be warranted.

Presently, some of the Upper Division States are exploring the feasibility of water banking concepts within the Upper Basin. A recommended next step is to continue to work with stakeholders in the Upper Basin regarding water banking concepts. Reclamation is committed to exploring creative and flexible ways to use storage facilities and other Reclamation infrastructure, consistent with authorized purposes and the Law of the River, in an attempt to accommodate appropriate water banking options. Moreover, the Upper Division States will engage in a broader conversation with the Lower Division States and other stakeholders, at the appropriate time, to discuss how an Upper Basin water bank would operate.

Water Transfers

In terms of reducing demands and as conservation options, water transfers were also demonstrated through the Study portfolios as being an important tool for resolving imbalances in the near and long-term. Voluntary water transfers can have many potential benefits and in particular promote flexibility in adapting to uncertain future conditions. Many of the Basin States have been utilizing voluntary water transfers within their respective states to meet water management challenges and will continue to look to transfers as an important solution. Although negative impacts can be associated with certain types of water transfers, such as permanent dry-up of agricultural land, innovative strategies can be employed to avoid these impacts and are being explored by many states. The Western Governors' Association's (WGA) recent report on water transfers identifies innovative approaches and specific steps that states can consider in order to improve water transfer outcomes (WGA, 2012). Reclamation will engage with the Basin States as appropriate to improve opportunities for water transfers and develop third party impact reduction and mitigation techniques that can be applied throughout the Basin.

Water Supply Augmentation

Large-scale water supply augmentation projects could provide additional reliable water to meet future demands, although such projects face significant permitting challenges and currently are both expensive and energy intensive. The assessments of large-scale water supply augmentation projects conducted in the Study were strictly at an appraisal level; additional study is needed to better understand the appropriate timing of investments, effectiveness, and tradeoffs.

Recommended next steps include identifying and defining appropriate feasibility-level studies for large-scale augmentation projects most likely to overcome the challenges previously noted. Prior to conducting feasibility-level studies, key stakeholders would come together to review scopes of work and develop funding and cost-sharing for the studies.

Watershed Management

There were a number of watershed management activities that were explored in the Study. Two of these activities were weather modification and vegetation management. Weather modification is inexpensive and has the potential to increase the Basin's supply. Several of the Basin States have funded weather modification activities on an ongoing basis for many years. Nevertheless, significant uncertainty exists related to the effectiveness of snowpack augmentation activities to increase available water supply. In addition, there is also significant uncertainty related to the long-term reliability of the option due to its reliance on current weather patterns, which may not persist under climate change scenarios. Enhanced understanding of weather modification is needed including the certainty of measured efficacy within targeted watershed.

Recommended next steps include the application of existing operational experience and research to identify target watersheds for snowpack augmentation activities, and continuation of research to reduce water supply yield uncertainties.

Vegetation management activities are ongoing at the state and local level. Most of these activities occur with the help of local partners, such as the Tamarisk Coalition. These activities should continue and be encouraged into the future.

Mitigation of dust on snow as an opportunity to increase water supply is a relatively new concept, and bears further exploration with federal partners including the Bureau of Land

Management. A dialogue among the relevant federal agencies and the appropriate Landscape Conservation Cooperatives (LCC) should be initiated to better understand the origins and mitigation options for managing dust on snow.

Tribal Water

The Indian Reserved Water Rights of the tribes of the Colorado River Basin are unique and have attributes that must be recognized under federal law and distinguished from state law water rights. The Indian Reserved Water Rights of the tribes of the Colorado River Basin account for approximately 2.9 million acre-feet of annual diversion rights of the total apportionment of the Colorado River in the United States. The Study does not fully account for Tribal water demand nor reflect the potential use of tribal water by others nor show the potential impact on the Basin water supply if a substantial amount of the presently unused or unquantified tribal water is used by the tribal water rights holders prior to 2060.

Working together with the Tribes, and recognizing the unique attributes of Indian Reserved Water Rights, Reclamation acknowledges that the outcome of tribal water settlements must be accounted for in Reclamation's analysis of water supply and demand, in order to accurately project imbalances in the Colorado River Basin. Indian Reserved Water Rights are unique under federal law, they are held in trust by the United States for the benefit of Tribes, and thus a trust obligation exists to protect those rights.

In particular, CRSS was intended to evaluate water availability in the Upper Basin and Lower Basin and potential water supply and demand imbalances through 2060. Reclamation acknowledges that the Study results are limited in their ability to fully account for the effects of tribal reserved water rights on projected supply and demand imbalances, in light of the unique attributes of those rights. The Study does, however, summarize quantified tribal water rights in *Technical Report C – Water Demand Assessment, Appendix C9 – Tribal Water Demand Scenario Quantification*, but Reclamation does not intend that the current Study be used to assess the future impacts to tribal water use in the Basin.

In light of the foregoing, and in recognition of the Federal Government's continued trust obligation to work with members of the Ten Tribes Partnership to protect their Tribal Reserved Water Rights, Reclamation and the Ten Tribes Partnership are committed to joint future planning efforts that build on the scientific foundation of the current Study and advance critical information beyond the limited assessment of tribal water in the Study. Future Reclamation planning efforts should include a study capable of evaluating full tribal development, control, and protection of tribal water resources in the Basin. This study should be conducted jointly by Reclamation and the Ten Tribes Partnership with involvement by interested stakeholders including the Basin States. Considerations should include water banking, voluntary water transfers, improved efficiencies, re-use opportunities, underground storage, and other options. These options may aid tribal and non-tribal users with developing options not presently available to respond to supply and demand uncertainty in the decades to come.

Reclamation also recognizes the importance of continued dialogue with respect to tribal matters at a regional and local level. In particular, several issues were identified by the Inter Tribal Council of Arizona in their option submission to the Study and these issues warrant further discussion. These issues are described in *Technical Report F – Development of Options and Strategies, Appendix F13 – Options Submitted by the Ten Tribes Partnership and the Inter Tribal Council of Arizona.* Reclamation is committed to participating actively in discussions with tribal leaders, continuing to seek resolution on these issues, and exploring opportunities that will bring the tribal perspective to bear in enhancing the management of the Basin resources.

Environmental Flows

The Study recognized the importance of considering river flows to support flow and water dependent ecological systems, power generation, and recreation, through its adoption of metrics used to approximate the performance of these resources, the inclusion of an Enhanced Environment water demand scenario, and the inclusion of a conceptual Upper Basin water bank the objective of which specifically includes improving the performance of ecological and recreational resources. Although these activities resulted in a good first step towards incorporating the needs of flow and water dependent ecological systems and exploring concepts to better meet those needs under a range of future conditions, exploring ways to meet ecological and recreational needs should continue beyond the completion of the Study. Future efforts should strive to better understand and quantify the needs of these systems, better reflect those needs in a modeling framework, and further explore solutions considered in the Study as well as others that promote the protection and improvement of environmental and recreational flows. The solutions should be explored in conjunction with those that support other management goals and decisions as to achieve integrated water management solutions that benefit multiple uses.

Recommended next steps focus on identifying potential enhancements to CRSS to improve the modeling of ecological, recreational, and power generation flow needs. Through an LCC grant in which The Nature Conservancy is the principal investigator, a workshop will be held in late summer 2013 to explore and recommend modeling improvements to appropriately consider recreational and environmental flow needs. Reclamation and the Basin States are committed to considering the recommendations that come from this workshop and to continue the dialogue with interested stakeholders to explore opportunities to include recreational and environmental flow needs in future water management decisions. This dialogue will be continued through the formation of an exploratory work group of interested stakeholders to identify and assess options that provide multiple benefits to improve flow and water dependent ecological systems, power generation, and recreation. The intent of this work group is not to focus on new regulatory requirements, but rather to identify opportunities for infrastructure, operations, and transactions that could reduce projected vulnerabilities resulting from future supply and demand imbalances.

Data and Tool Development

CRSS was the primary modeling tool utilized in the Study. Originally developed to model Lake Powell and Lake Mead operations, the Study demonstrated the need to improve the spatial resolution of CRSS, particularly in the Upper Basin. Improvements to CRSS are needed to better support future endeavors identified in these next steps, such as analysis of Upper Basin water banking concepts, enhanced modeling of environmental flows, and exploring tribal water development and options to resolve imbalances related to tribal water. The scoping and design of these improvements will occur through Reclamation’s Stakeholder Modeling Workgroup. This work will begin within a year of completion of the Study and may build on recommendations from the LCC workshop discussed above.

The Study has resulted in enhanced tools and datasets for water resource planning in the Basin. The Basin States will work with Reclamation to evaluate the ability to use the tools developed for the Study and update water demands and supply scenarios on a five-year timeframe. The

Basin States will work with Reclamation to support improvements in the Study's input information, modeling and analytical tools. The Basin States will also work with Reclamation in fulfilling the commitments regarding the Lower Basin tributaries specifically described in *Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System*.

Climate Science Research

The Study used the best available science at the time it was initiated. Nonetheless, climate science is rapidly evolving and a new set of GCM projections will soon be available. Next steps include prioritizing the research agenda of Reclamation's Hydrology Work Group to advance the technical foundation established by the Study regarding the use of climate projections in future studies.

Partnerships

The collaborative approach adopted by the Study was paramount to its success. Next steps should be taken in ways that build on its momentum and dialogue to increase the effectiveness of partnership responses when new challenges and opportunities arise. As in the past, the Federal Government can provide a leadership role in appropriate processes to facilitate this dialogue.

11.0 Summary of Next Steps

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.

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 availability issues 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.

12.0 References

Bureau of Reclamation (Reclamation). 2011a. SECURE Water Act Section 9503(c) – "Reclamation Climate Change and Water."

Bureau of Reclamation (Reclamation), 2011b. *Phase 4: Development and Evaluation of Opportunities for Balancing Water Supply and Demand – Request for Ideas*.

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

Bureau of Reclamation (Reclamation). 1996. *Operation of Glen Canyon Dam Final Environmental Impact Statement*.

Bureau of Reclamation (Reclamation). 1975. *Westwide Study Report on Critical Water Problems Facing the Eleven Western United States*. April.

Bureau of Reclamation (Reclamation). 1964. *Pacific Southwest Water Plan*. January.

Bureau of Reclamation (Reclamation). 1950. *Colorado River Storage Project and Participating Projects; Upper Colorado River Basin.* September.

California Building Standards Commission. 2010. California Plumbing Code.

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 Sci*., 11:1417–1434.

Colorado River Water Consultants. 2008. *Study of Long-Term Augmentation Options for Water Supply of the Colorado River System*.

Hoerling, M., D. Lettenmaier, D. Cayan, and B. Udall. 2009. "Reconciling Future Colorado River Flows." *Southwest Hydrology,* 8(3).

Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. ISBN 92-9169-122-4. Retrieved from http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm.

Liang, X., D.P. Lettenmaier, and E.F. Wood. 1996. *Surface Soil Moisture Parameterization of the VIC-2L Model: Evaluation and Modification*.

Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges. 1994. "A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models." *Journal of Geophysical Research*, Vol. 99, 14415–14428.

Maurer, E.P., L. Brekke, T. Pruitt, and P.B. Duffy. 2007. "Fine-resolution climate projections enhance regional climate change impact studies." *Eos Trans. AGU*, 88(47), 504.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15(22), 3237-3251.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughs, and M.W. Salzer. 2007. "Medieval drought in the Upper Colorado River Basin." *Geophysical Research Letters* 2007 34(5), L10705, DOI: 10.1029/2007GL029988.

National Research Council. 2007. *Colorado River Basin Water Management – Evaluating and Adjusting to Hydroclimate Variability*. The National Academies Press.

Nijssen, B., D.P. Lettenmaier, X. Liang, S.W. Wetzel, and E.F. Wood. 1997. "Streamflow simulation for continental-scale river basins." *Water Resource Research*, 33, 711–724.

Ouarda, T., D. Labadie, and D. Fontare. 1997. "Indexed Sequential Hydrologic Modeling for Hydropower Capacity Estimates." *Journal of the American Water Resources Association*, Vol. 33, No. 6. December.

Pacific Southwest Inter-agency Committee. 1971a. *Comprehensive Framework Study, Lower Colorado Region*. Prepared by the Lower Colorado Region State – Federal Interagency Group for the Pacific Southwest Inter-agency Committee, Water Resources Council. June.

Pacific Southwest Inter-agency Committee. 1971b. *Comprehensive Framework Study, Upper Colorado Region*. Prepared by the Upper Colorado Region State – Federal Interagency Group for the Pacific Southwest Inter-agency Committee, Water Resources Council. June.

Painter, T. H., A. P. Barrett, C. C. Landry, J. C. Neff, M. P. Cassidy, C. R. Lawrence, K. E. McBride, and G. L. Farmer. 2007. "Impact of disturbed desert soils on duration of mountain snow cover." *Geophys. Res. Lett*., 34, L12502, doi:10.1029/2007GL030284.

Painter T, Deems J, Belnap J, Hamlet A, Landry C, and Udall B. 2010. "Response of Colorado River runoff to dust radiative forcing in snow." Proceedings of the National Academy of Sciences.

Painter, T. H., S. M. Skiles, J. S. Deems, A. C. Bryant, and C. C. Landry. 2012. "Dust Radiative Forcing in Snow of the Upper Colorado River Basin: 1. A 6 Year Record of Energy Balance, Radiation, and Dust Concentrations." *Water Rour. Res*., 48, W07521, doi:10.1029/2012WR011985.

Skiles, S. M., T. H. Painter, J. S. Deems, A. C. Bryant, and C. C. Landry. 2012. "Dust radiative forcing in snow of the Upper Colorado River Basin: 2. Interannual variability in radiative forcing and snowmelt rates" *Water Resour. Res*., 48, W07522, doi:10.1029/2012WR011986.

Stephens, J., and E. Stewart. Circa 1960. *A Comparison of Procedures for Computing Evaporation and Evapotranspiration.* International Association of Hydrologic Sciences. Retreived from http://iahs.info/redbooks/a062/iahs_062_0123.pdf.

Timpe, C., and M.J.J. Scheepers. 2003. *SUSTELNET: A Look into the Future: Scenarios for Distributed Generation in Europe*.

U.S. Department of the Interior (DOI). 2007. Record of Decision for Colorado River Basin Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead.

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 was constrained by funding, timing, and technological and other limitations, and in some cases presented 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 developed and incorporated assumptions to further complete the Study. Where possible, a range of assumptions was typically 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.

Appendix A1
Driving Forces Survey

Appendix A1 — Driving Forces Survey

1.0 Instructions/Guidance for Completing the Colorado River Basin Water Supply and Demand Study Driving Forces Survey

1.1 Survey Objectives

The Plan of Study, provided in Driving forces represent the key factors that affect the reliability of the Colorado River system over time. The attached survey is intended to receive input from representatives of water agencies, other federal and state agencies, Native American Tribes and communities, other stakeholders, and other experts on the relative importance and uncertainty of each of the driving forces over the next 50 years. The overall objective of the survey is to identify the critical uncertainties that will form the basis of storylines and scenarios for the Colorado River Basin Water Supply and Demand Study (Study). Critical uncertainties are key driving forces that are both highly important and highly uncertain.

The purpose and objectives for the Study can be expressed in two fundamental questions:

1. What is the future reliability of the Colorado River system to meet the needs of Basin resources through 2060?
2. What are the options and strategies to mitigate future risks to these resources?

The first question relates directly to incorporating uncertainty and is the focus of the scenario development process. This survey is an important element in that process. The second question relates to management responses to the potential impacts under uncertain futures and is the focus of the water management option and strategy development. This question will be addressed in the "options and strategies" phase of the Study.

1.2 Survey Format

The survey includes a list of driving forces that influence the future reliability of the Colorado River system. The respondent is requested to independently rate (using a scale of 1 through 5, with 5 being the highest) the relative "importance" and "uncertainty" associated with each driving force with respect to the key question or focal issue of the Study being addressed through the scenario development process:

- **Importance (1 through 5):** Rate the relative importance of the driving forces to the reliability of the Colorado River system to meet the needs of Basin resources through 2060
- **Uncertainty (1 through 5):** Rate the relative uncertainty of the driving forces in the Colorado River Basin through 2060

The respondent is encouraged to provide comments related to each response. Such comments will help the Study Team better analyze the data received, particularly for high and low ratings.

1.3 Guidance for Completing the Survey

The driving forces list is intended to be relatively broad to capture the large-scale mechanisms that influence the system reliability. Not every variation on a driving force category is necessary at this point in the scenario development process as details of the critical uncertainties will be explored in the next steps of the scenario development process. However, please provide any comments you have that may help us better understand your views regarding a particular driving force.

Some additional guidance may be helpful in the completion of the survey:

1. Relate all ratings to the key question/focal issue
   a. What is the reliability of the Colorado River system to meet the needs of Basin resources through 2060?
2. Consider the current influence of the driving force in addition to evolving trends and the range of effects of the driving force through 2060
   a. How important is the driving force on the system today? What are the current trends in these forces? Are the future trends likely to following the same trajectory? What is the magnitude of these influences?
3. Distinguish between "external" factors (i.e., those factors that are largely outside of the control of water management entities) and "internal" factors (i.e., those factors that are largely within the control of water management entities and will be addressed in the "options and strategies" phase of the Study)
   a. Consider each factor in the context of the forces that are largely "external" to the control of water management entities.
4. Keep your ratings of importance and uncertainty separate
   a. Importance is a relative measure of the magnitude of the influence of a driving force on system reliability.
   b. Uncertainty is a relative measure of the likelihood of occurrence of the driving force over the planning horizon.
5. Keep in mind that the survey is a relative comparison
   a. You may wish to make two passes through the survey—the first to gauge an initial baseline and the second to align the relative rating of all driving forces.

1.4 Complete and Return the Survey

Please complete the survey, indicating 1 through 5 in the “importance” and “uncertainty” columns for each driving force. Please add comments that will help to convey the reasons for and the intent of a specific rating.

The survey responses can either be typed directly into the form or filled out by hand.

Please return the survey to Amber Cunningham via email (AZCunningham@usbr.gov) or fax to (702) 293-8156 by 12:00 PM PDT on Thursday August 26.

Please call Amber at (702) 293-8472 if you have questions/problems.

TABLE A1-1
Table of Driving Forces and Survey Relating to Importance and Uncertainty

Name/Organization (optional):
Importance (1–5): Rate the relative importance of the driving forces to the reliability of the Colorado River system to meet the needs of Basin resources through 2060
Uncertainty (1–5): Rate the relative uncertainty of the driving forces in the Colorado River Basin through 2060
Importance Rating Guidance: 1=Relatively Unimportant, 3=Important, 5=Extremely Important
Uncertainty Rating Guidance: 1=Relatively Certain, 3=Uncertain, 5=Highly Uncertain
NA=Enter “NA” if you are unfamiliar with the driving force (Note: will not be included in final rating)

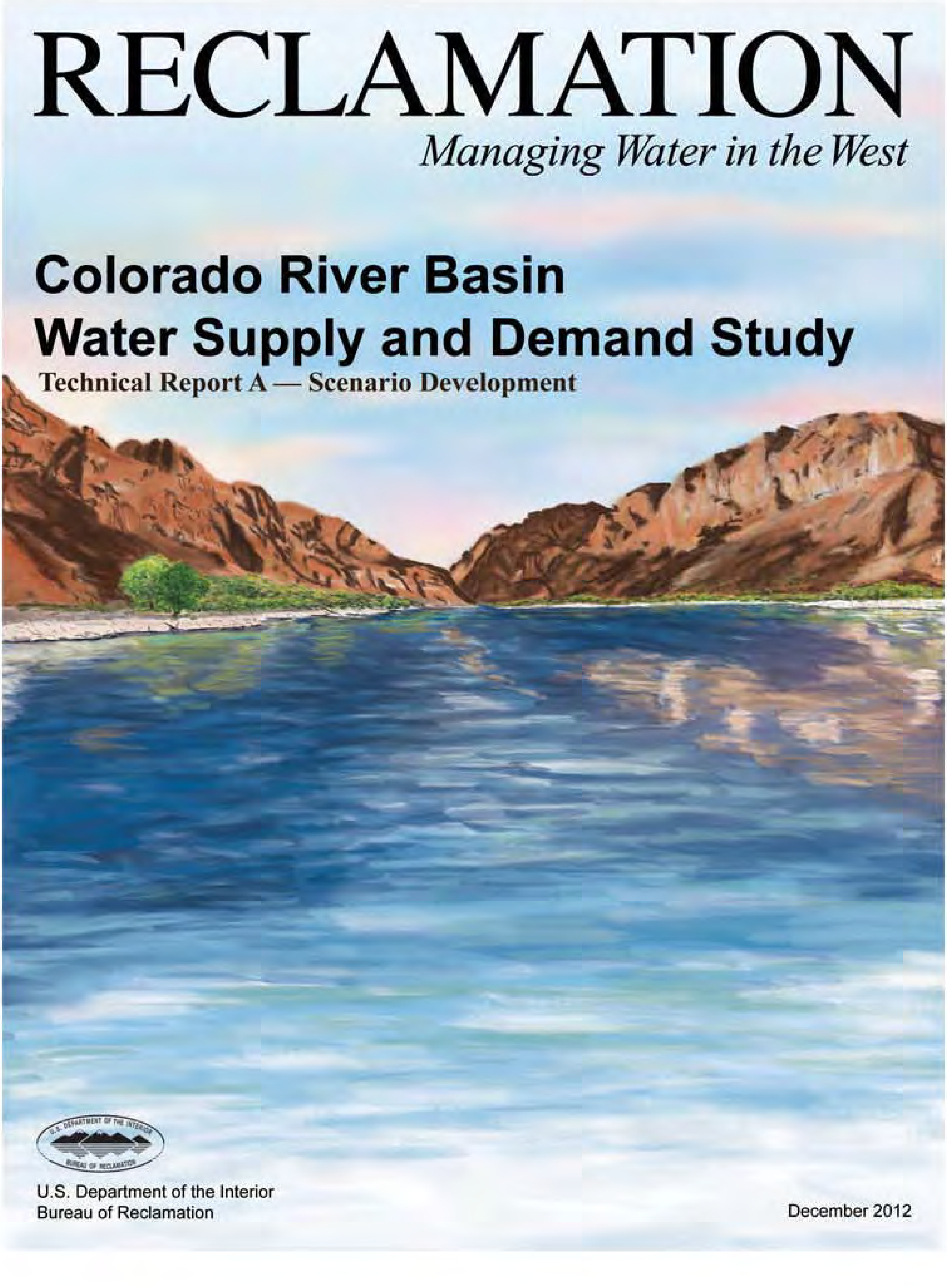
No.	Driving Forces	Importance	Uncertainty	Comment
1	Changes in streamflow variability and trends			
2	Changes in climate variability and trends (e.g., temperature, precipitation, etc.)			
3	Changes in watershed conditions (e.g., diseases, species transitions, etc.)			
4	Changes in population and distribution			
5	Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes, etc.)			

Table continued on next page

No.	Driving Forces	Importance	Uncertainty	Comment
6	Changes in urban land use (e.g., conversion, density, urbanization, etc.)			
7	Changes in public land use (e.g., forest practices, grazing, wilderness areas, etc.)			
8	Changes in agricultural water use efficiency			
9	Changes in municipal and industrial water use efficiency			
10	Changes in institutional and regulatory conditions (e.g., laws, regulations, etc.)			
11	Changes to organization or management structures (e.g., state, federal, bi-national institutions, etc.)			
12	Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear, etc.)			
13	Changes in flow-dependent ecosystem needs for ESA-listed species			
14	Changes in other flow-dependent ecosystem needs			

Table continued on next page

No.	Driving Forces	Importance	Uncertainty	Comment
15	Changes in social values affecting water use			
16	Changes in cost of energy affecting water availability and use			
17	Changes in water availability due to tribal water use and settlement of tribal water rights claims			
18	Changes in water quality including physical, biological, and chemical processes			



RECLAMATION

Managing Water in the West

Colorado River Basin Water Supply and Demand Study

Technical Report A — Scenario Development

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

Technical Report A — Scenario Development

U.S. Department of the Interior
Bureau of Reclamation

December 2012

Contents

Tables

Figures

Appendix

Acronyms and Abbreviations

Basin	Colorado River Basin
Basin States	Colorado River Basin States
ESA	Endangered Species Act
GCM	General Circulation Model
Mexico	United Mexican States
Reclamation	Bureau of Reclamation
Study	Colorado River Basin Water Supply and Demand Study
tribes	federally recognized tribes

Technical Report A — Scenario Development

1.0 Introduction

The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). The purpose of the Study is 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 contains for major phases to accomplish this goal: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for Balancing Supply and Demand.

Spanning parts of the seven states of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, the Colorado River is one of the most critical sources of water in the western United States. The Colorado River is also a vital resource to the United Mexican States (Mexico). It is widely known that the Colorado River, based on the inflows observed over the last century, is over-allocated and supply and demand imbalances are likely to occur in the future. Up to this point, this imbalance has been managed, and demands have largely been met as a result of the considerable amount of reservoir storage capacity in the system, the fact that the Upper Basin States are still developing into their apportionments, and efforts the Basin States have made to reduce their demand for Colorado River water.

Concerns regarding the reliability of the Colorado River system to meet future needs are even more apparent today. The Basin States include some of the fastest growing urban and industrial areas in the United States. At the same time, the effects of climate change and variability on the Basin water supply has been the focus of many scientific studies which project a decline in the future yield of the Colorado River. Increasing demand, coupled with decreasing supplies, will certainly exacerbate imbalances throughout the Basin.

It is against this backdrop that the Study was conducted to establish a common technical foundation from which important discussions can begin regarding possible strategies to reduce future supply and demand imbalances. The content of this report is a key component of that technical foundation and describes the Study's scenario planning process.

The amount of water available and the progression of demand for water in the Basin (and the adjacent areas of the Basin States that receive Colorado River water) over the next 50 years are highly uncertain and dependent upon a number of socioeconomic and other factors. The potential impacts of future climate variability and climate change further contribute to these uncertainties. To analyze the future reliability of the Colorado River system, with and without adaptation and mitigation strategies, projections of water supply and demand were necessary. These projections needed to be sufficiently broad to capture the plausible ranges of uncertainty in future water supply and water demand to ensure that the reliability of the Colorado River system was adequately analyzed.

A scenario planning process was used to guide the development of scenarios that provided a broad range of projections of future water supply and demand. The process involved the identification of the key forces that will likely drive future water supply and water demand, ranking of the driving forces as to their relative importance and uncertainty, and use of the highly uncertain and highly important driving forces to identify various themes and storylines (narrative descriptions of scenarios) that describe how water supply and water demand may evolve in the future. Quantification of the storylines resulted in water supply and water demand scenarios that were used to assess future system reliability and assess the performance of options and strategies.

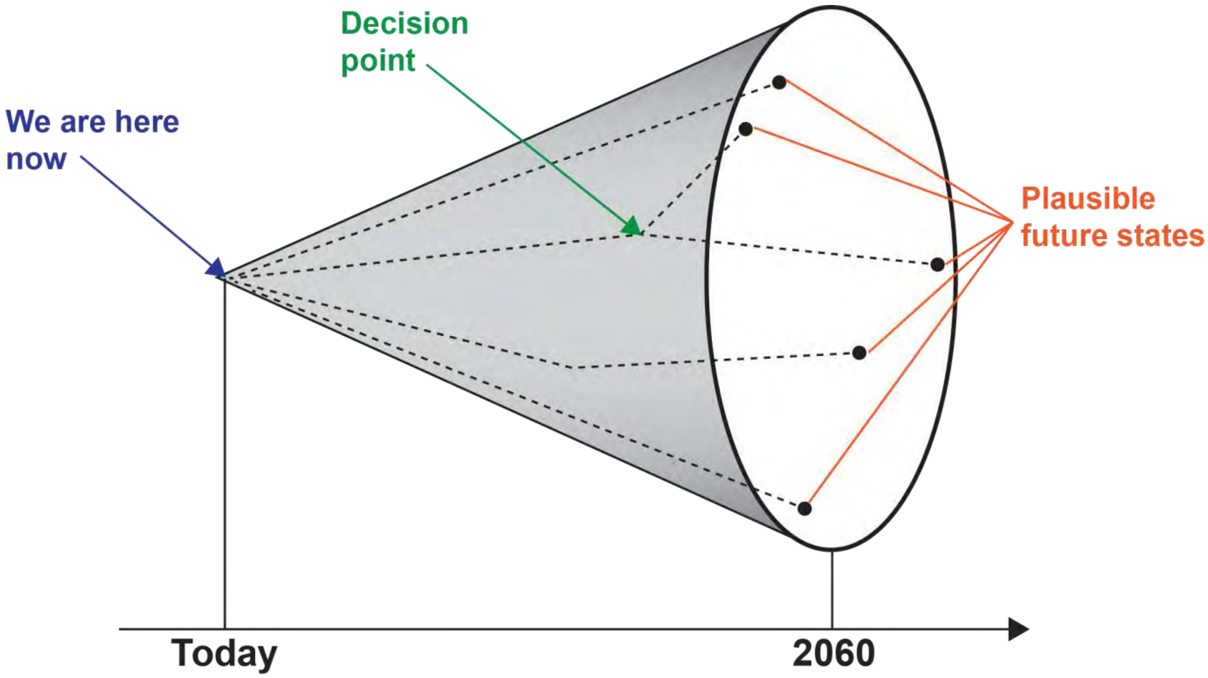
This report provides background on scenario planning and describes the scenario development approach used in the Study to develop the water supply and demand scenarios. Initially published in June 2011 under Interim Report No. 1, this report replaces the earlier publication. Four water supply scenarios and six water demand scenarios were identified and quantified. Details regarding the quantification and analysis of the water supply and water demand scenarios are presented in the respective technical reports (*Technical Report B – Water Supply Assessment,* and *Technical Report C – Water Demand Assessment*).

2.0 Incorporating Uncertainty in Water Resources Planning

Management of water resources, and particularly those of the Colorado River, is a complex interplay between natural and human systems, driven by forces such as climatic, demographic, economic, social, institutional, political, and technological factors. The precise trajectory of this interplay over time, and the resulting state of the physical system over time, are uncertain and cannot be represented by a single view of the future. In light of this broad uncertainty, scenario planning can be used to consider and portray the broad range of plausible futures in a manageable number of scenarios. Scenario approaches have been widely applied in water planning and management, from global to regional scales, although specific methodologies have varied considerably (Alcamo and Gallopin, 2003; Mara and Thomure, 2009; Water Utility Climate Alliance, 2010).

Scenarios are alternative views of how the future might unfold. Scenarios are not predictions or forecasts of the future. Rather, a set of well-constructed scenarios represents a range of plausible futures that assists in the assessment of future risks and the development of mitigation and adaptation options and strategies. Figure A-1 shows this concept. At present, there is an understanding of the current state of the Colorado River system. For the future, a range of plausible futures, represented by the funnel, can be identified. The suite of scenarios used in the planning effort should be sufficiently broad to span the plausible range.

FIGURE A-1
Conceptual Representation of the Uncertain Future of a System, also known as "The Scenario Funnel"
(adapted from Timpe and Scheepers, 2003)



3.0 Overview of Scenario Planning Process

Figure A-2 presents the general steps involved in the scenario planning process as applied to a water resources planning study, from the initial point of framing the focal question(s) being addressed by the study, through the development and analysis of options and strategies to improve system performance.

The shaded area within figure A-2 encapsulates the steps that are typically part of the development of scenarios, and are the focus of this report.

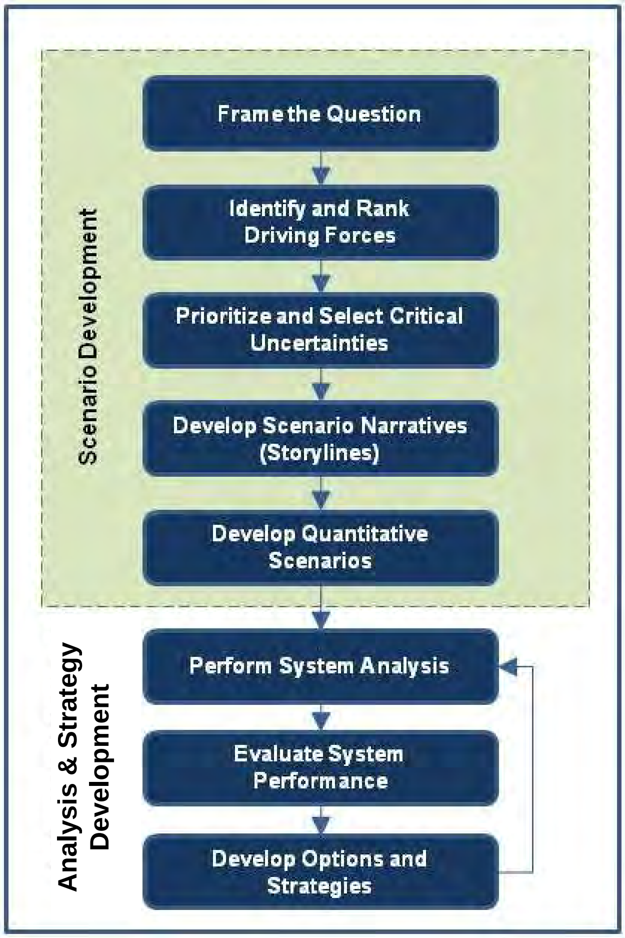
Input from a broad sampling of stakeholders, experts, and others interested in the management of the system was crucial throughout the development of scenarios. This input ensured that the resulting scenarios were representative of the plausible range of futures in the view of those who best know the system.

The five steps shown in figure A-2 for typical scenario development are described below.

3.1 Frame the Question

The scenario planning process begins with a clear understanding of the purpose and objectives of the planning study. Defining the focal question of the study is crucial to the development of scenarios and options and strategies. The focal question (or questions) is the key question or issue that the study wishes to address, and provides the framework for the consideration of the key forces that influence future uncertainty.

FIGURE A-2
General Steps Involved in the Scenario Planning Process



3.2 Identify and Rank Driving Forces

Driving forces are the factors that will likely have the greatest influence on the future state of the system and thereby the performance of the system over time. Although the driving forces that have been considered in water management studies have varied, driving forces within the following categories have generally been considered:

- Natural Systems
- Demographic
- Economic
- Technological
- Social
- Governance

Not all driving forces influence the system to the same degree or contribute the same level of uncertainty. In the development of scenarios, it is useful to rank each driving force based on its relative importance to the focal questions of the study and the relative degree of uncertainty of that driving force over time.

3.3 Prioritize and Select Critical Uncertainties

Critical uncertainties are the key driving forces that are identified as both highly uncertain and highly important. Stakeholder and other expert input is crucial for identifying these critical uncertainties to gauge the relative “importance” and “uncertainty” of each of the driving forces. This input can be gathered in various ways, such as holding workshops, conducting surveys, or using other outreach methods. The critical uncertainties can be identified from the expert input and other outreach, and a number of critical uncertainties are selected to form the basis for storyline development.

3.4 Develop Storylines

A storyline is the narrative description of a scenario, based on the critical uncertainties; the storyline provides the “plot” of the scenario. Development of storylines is a qualitative process, requiring the involvement of subject matter experts who have the best understanding of the system and of the critical uncertainties.

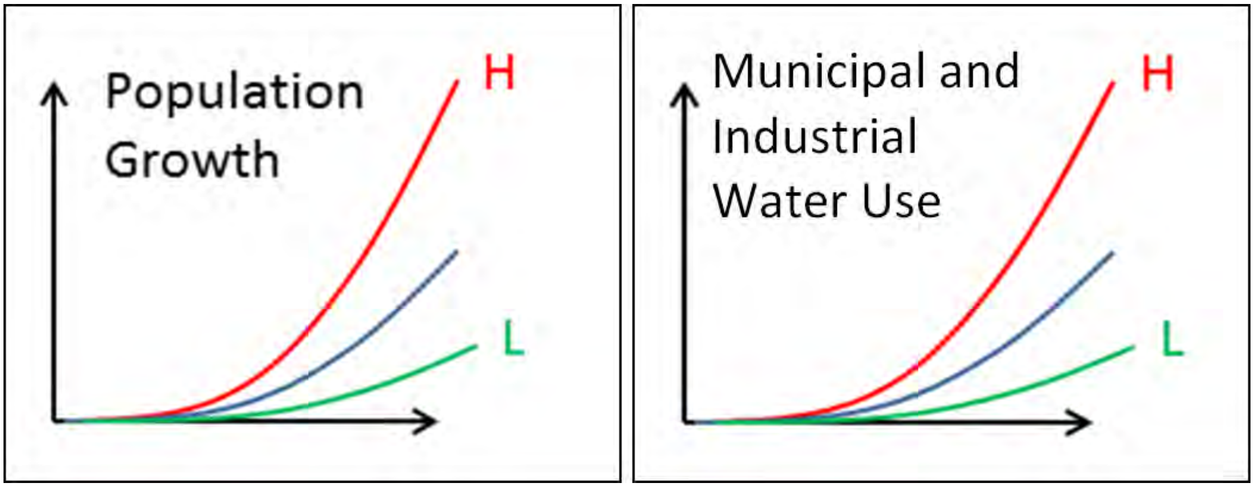
The process of developing the storylines requires identifying parameters that describe each critical uncertainty, characterizing the evolution of those parameters over time, and combining the characteristics of various parameters into descriptions of plausible futures.

Parameters are the variables that describe the behavior of a critical uncertainty. For example, for the critical uncertainty Changes in Population and Distribution, the parameters include “population” and “population distribution.” Once the parameters have been identified, the plausible range of each parameter over time is described.

Figure A-3 shows a hypothetical high-, low-, and medium-growth curve for the key parameter, “population” on the left, and a similar hypothetical plot for the parameter, “municipal and industrial water use efficiency” parameter on the right. For each parameter, the curves represent qualitative characteristics describing plausible future trajectories. The two parameters in figure A-3 are descriptors of two separate critical uncertainties identified in the Study, Changes in Population Growth and Distribution and Changes in Municipal and Industrial Water Use Efficiency, respectively.

In the development of the storylines, the critical uncertainties and associated parameter characteristics are combined based on logical, coherent descriptions of how the future may unfold. For example, high population growth may be envisioned with modest or large increases in water use efficiency as part of a particular storyline. As a result of this process, the storyline and its logic should be understandable to a broad range of stakeholders. Furthermore, an understanding of the combination of parameter characteristics in a given storyline assists in the subsequent step of quantifying the scenario.

FIGURE A-3
Example of the Qualitative Characterization of Critical Uncertainties



3.5 Develop Quantitative Scenarios

Scenarios are the result of quantifying the parameter characteristics that are described in the storylines. As is the case with other steps in the scenario development process, stakeholder and other expert input is important to ensure that the resulting scenario depicts the appropriate range of each parameter as described in the storyline.

For example, in the case of population growth, there may be differing views as to what constitutes high, medium, and low growth. Dialogue is necessary to ensure a common understanding of the storyline's meaning and its subsequent quantification.

In some cases, scenarios make use of quantitative information previously developed to address uncertainties. In these cases, the existing information is reviewed and checked for consistency with the assumptions and storyline process.

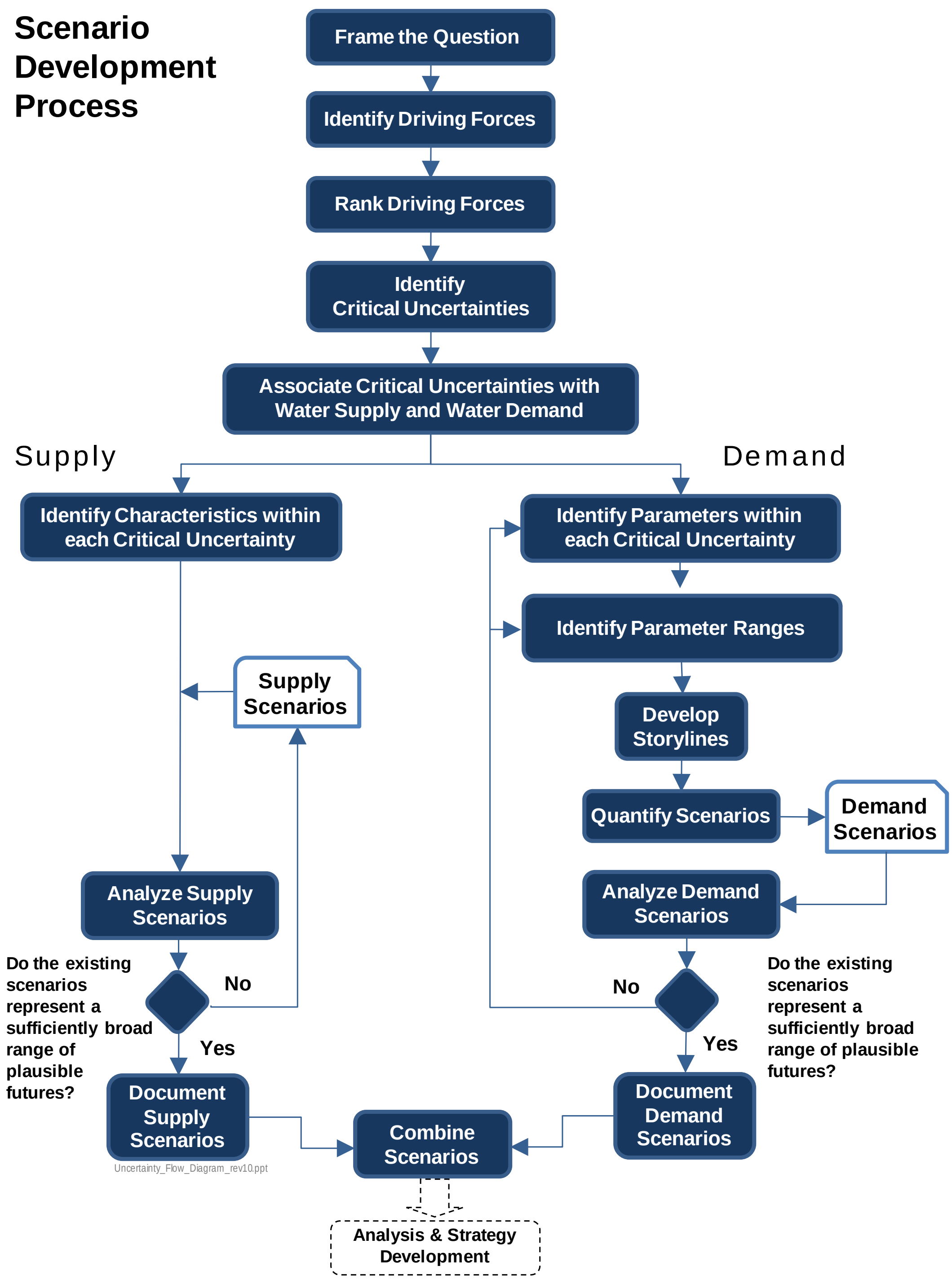
Well-understood and well-documented scenarios are critical to implementing the process depicted in figure A-2.

4.0 Implementation of Scenario Development Process

The general steps involved in scenario planning are shown in figure A-2, and they provided the framework for the approach implemented in the Study. To specifically address the needs of the Study, this approach was customized and is shown in figure A-4. This section describes the specific steps undertaken in the Study.

A collaborative process that engaged stakeholders was essential to the successful development of scenarios. For the Study, representatives of numerous organizations participated, including the Bureau of Reclamation (Reclamation), the Basin States, U.S. Fish and Wildlife Service, National Park Service, Bureau of Land Management, Western Area Power Administration, federally recognized tribes (tribes), conservation organizations, water delivery contractors, contractors for the purchase of federal power, and others interested in the Basin. This collaboration was accomplished through a variety of means, including workshops, surveys, and participation in sub-teams.

FIGURE A-4
Scenario Development Process Used in the Study



4.1 Frame the Question

The purpose and objectives defined in the *Plan of Study* (see *Study Report, Appendix 1 – Plan of Study*) were used to frame the focal questions that the Study addressed. These questions are:

1. What is the future reliability of the Colorado River system to meet the needs of Basin resources through 2060?
2. What are the options and strategies to mitigate future risks to these resources?

The first question requires an understanding of the underlying components of future reliability: water supply and water demand. Specifically, what factors determine the future availability of water and what factors that determine the future demand for water? The scenario development process addressed these questions and resulted in scenarios of the future that define a range of plausible water supply and water demand outcomes.

The second question relates to water management responses to mitigate and adapt to the potential impacts to Basin resources under scenarios of the future, and was the focus of the analysis and strategy development phases of the Study.

4.2 Identify Driving Forces

An initial list of 14 specific driving forces relevant to understanding potential future conditions was developed using the general categories previously described, based on experience managing the Colorado River system. Stakeholder teleconferences were conducted to seek input to refine and add to the initial list of driving forces. The stakeholder outreach was conducted by the Water Supply, Water Demand, and System Reliability Metrics Sub-Teams, and included members from water management entities, federal resource management agencies (fishery, recreation, energy, and land management), tribes, and conservation organizations. The input from these stakeholders expanded the initial list of driving forces from 14 to 18 and resulted in greater clarity in the definition of some driving forces. Table A-1 lists the driving forces. The numbers were assigned for identification purposes only and do not imply priority.

4.3 Rank Driving Forces

Stakeholder and other expert input regarding the critical uncertainties was collected by conducting a survey (see appendix A1). The survey listed the 18 driving forces (table A-1) and asked the respondents to independently rate (using a scale of 1 through 5, with 5 being the highest) the relative importance and relative uncertainty associated with each driving force. Specifically, the respondents were asked to provide ratings based on the following two characteristics:

- **Importance (1 through 5)**: Rate the relative importance of the driving forces to the reliability of the Colorado River system to meet the needs of Basin resources through 2060
- **Uncertainty (1 through 5):** Rate the relative uncertainty of the driving forces in the Colorado River Basin through 2060

TABLE A-1
List of Driving Forces Influencing Future Colorado River System Reliability

No.	Driving Force
1	Changes in streamflow variability and trends
2	Changes in climate variability and trends (e.g., temperature, precipitation, etc.)
3	Changes in watershed conditions (e.g., diseases, species transitions, etc.)
4	Changes in population and distribution
5	Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes, etc.)
6	Changes in urban land use (e.g., conversion, density, urbanization, etc.)
7	Changes in public land use (e.g., forest practices, grazing, wilderness areas, etc.)
8	Changes in agricultural water use efficiency
9	Changes in municipal and industrial water use efficiency
10	Changes in institutional and regulatory conditions (e.g., laws, regulations, etc.)
11	Changes to organization or management structures (e.g., state, federal, bi-national institutions)
12	Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear, etc.)
13	Changes in flow-dependent ecosystem needs for Endangered Species Act (ESA)-listed species
14	Changes in other flow-dependent ecosystem needs
15	Changes in social values affecting water use
16	Changes in cost of energy affecting water availability and use
17	Changes in water availability due to tribal water use and settlement of tribal water rights claims
18	Changes in water quality including physical, biological, and chemical processes

The respondents were encouraged to provide comments related to each response to aid in understanding the context of high or low responses. In addition, guidance was provided to the respondents relating to the first focal question and to the Study period (through 2060), consideration of current and evolving trends, and external versus internal factors.

The survey was sent to all who participated in the driving forces list review and refinement. Some entities sought further input from their respective technical staffs and/or stakeholders. Respondents could respond to the survey anonymously, if desired, but their respective affiliation category was entered into a database. A total of 51 survey responses were received, with the affiliation category distribution as shown in table A-2. Water management entities comprised more than half of the responses, and conservation organizations, fishery management entities, and recreation entities represented approximately one-third of the responses.

TABLE A-2
Summary of Respondent Affiliation Category for the Driving Force Uncertainty Survey

Respondent Category	No. of Responses Received
Water Management Entities (including Reclamation)	28
Conservation Organizations	9
Fishery Management Entities	3
Federally Recognized Tribes and Communities	3
Water Resources Contractors	3
Recreation Management Entities	2
Energy Management Entities	2
Land Management Entity	1
Total	**51**

The individual survey responses were compiled into a database, and the mean and standard deviation were computed for each driving force, as shown in table A-3. Driving forces that had the highest mean responses were classified as highly important and highly uncertain. The driving forces, “changes in streamflow variability and trends” (No. 1) and “changes in climate variability and trends” (No. 2), consistently ranked high in both importance and uncertainty. Similarly, “changes in population and distribution” (No. 4), consistently ranked high in importance. Although the sample size was relatively small for evaluating statistics, the standard deviation provided a measure of the differences in responses among the respondents. “Changes in streamflow variability and trends” (No. 1) was considered important by most respondents, as represented by a small standard deviation, whereas “changes in institutional and regulatory conditions” (No. 10) and “changes to organization or management Structures” (No. 11) had a wide range of responses in both importance and uncertainty.

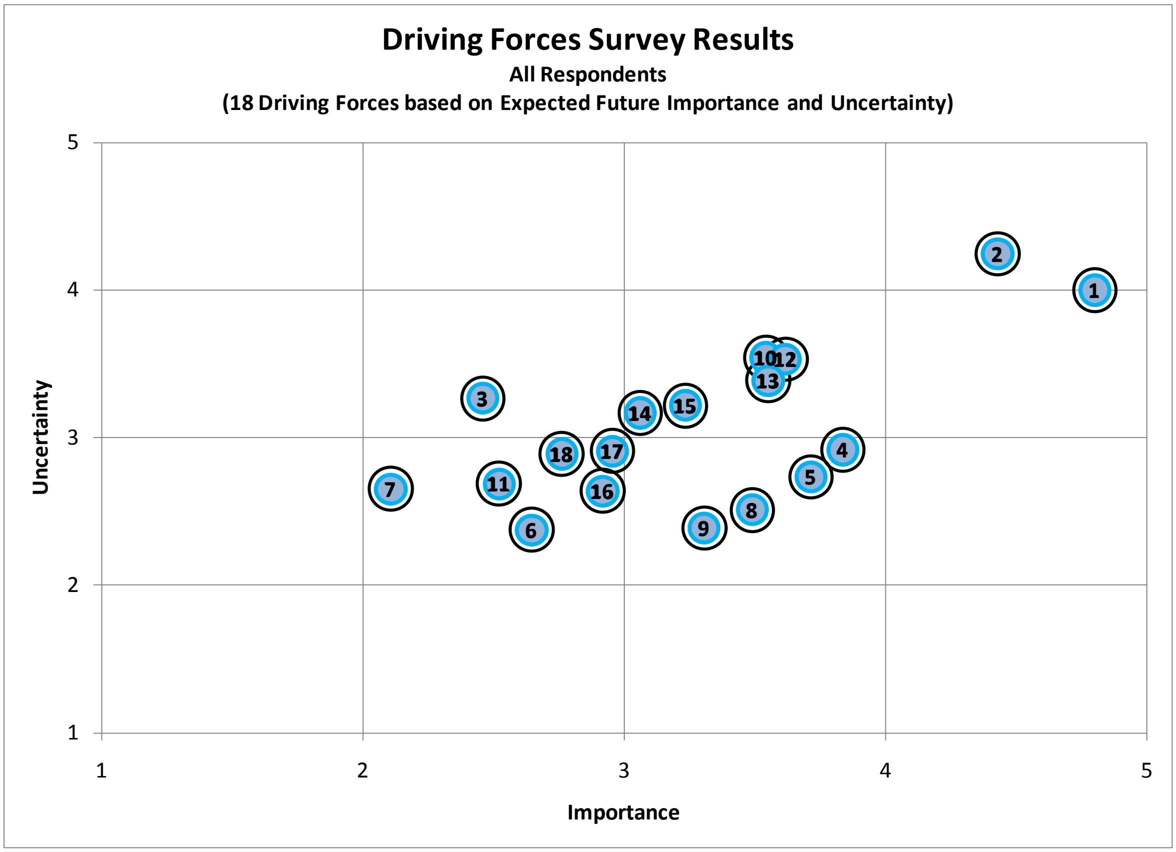
The results of the survey are also displayed in figure A-5. In this figure, the numbers are the driving forces listed in table A-1 and the plotting position is determined by the relative importance and relative uncertainty based on the mean of all survey responses. Driving forces that plotted to the upper right were believed to be highly important and highly uncertain, and those that plotted to the lower left were perceived by the respondents to be of lesser importance and lower uncertainty. The driving forces that plotted to the lower right were perceived to be of high importance, but had less uncertainty.

TABLE A-3
Summary of Responses for the Driving Forces Survey[1]

No.	Driving Force	Importance Mean	Importance Std Dev	Uncertainty Mean	Uncertainty Std Dev
1	Changes in streamflow variability and trends	4.80	0.53	4.00	1.12
2	Changes in climate variability and trends (e.g., temperature, precipitation, etc.)	4.43	0.94	4.24	1.01
3	Changes in watershed conditions (e.g., diseases, species transitions, etc.)	2.46	1.10	3.27	0.88
4	Changes in population and distribution	3.84	0.96	2.92	1.08
5	Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes, etc.)	3.71	1.17	2.73	1.00
6	Changes in urban land use (e.g., conversion, density, urbanization, etc.)	2.65	0.96	2.38	1.02
7	Changes in public land use (e.g., forest practices, grazing, wilderness areas, etc.)	2.11	0.94	2.65	0.99
8	Changes in agricultural water use efficiency	3.49	1.19	2.51	0.87
9	Changes in municipal and industrial water use efficiency	3.31	1.12	2.39	0.84
10	Changes in institutional and regulatory conditions (e.g., laws, regulations, etc.)	3.54	1.24	3.54	1.25
11	Changes to organization or management structures (e.g., state, federal, bi-national institutions)	2.52	1.25	2.69	1.22
12	Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear, etc.)	3.62	1.11	3.53	1.08
13	Changes in flow-dependent ecosystem needs ESA-listed species	3.55	1.00	3.39	1.11
14	Changes in other flow-dependent ecosystem needs	3.06	1.13	3.17	1.19
15	Changes in social values affecting water use	3.23	1.22	3.22	1.23
16	Changes in cost of energy affecting water availability and use	2.92	1.16	2.64	1.22
17	Changes in water availability due to tribal water use and settlement of tribal water rights claims	2.95	1.18	2.91	1.05
18	Changes in water quality, including physical, biological, and chemical processes	2.76	1.25	2.89	1.27

[1] Respondent survey rating scale of 1 to 5, with 5 being the highest.

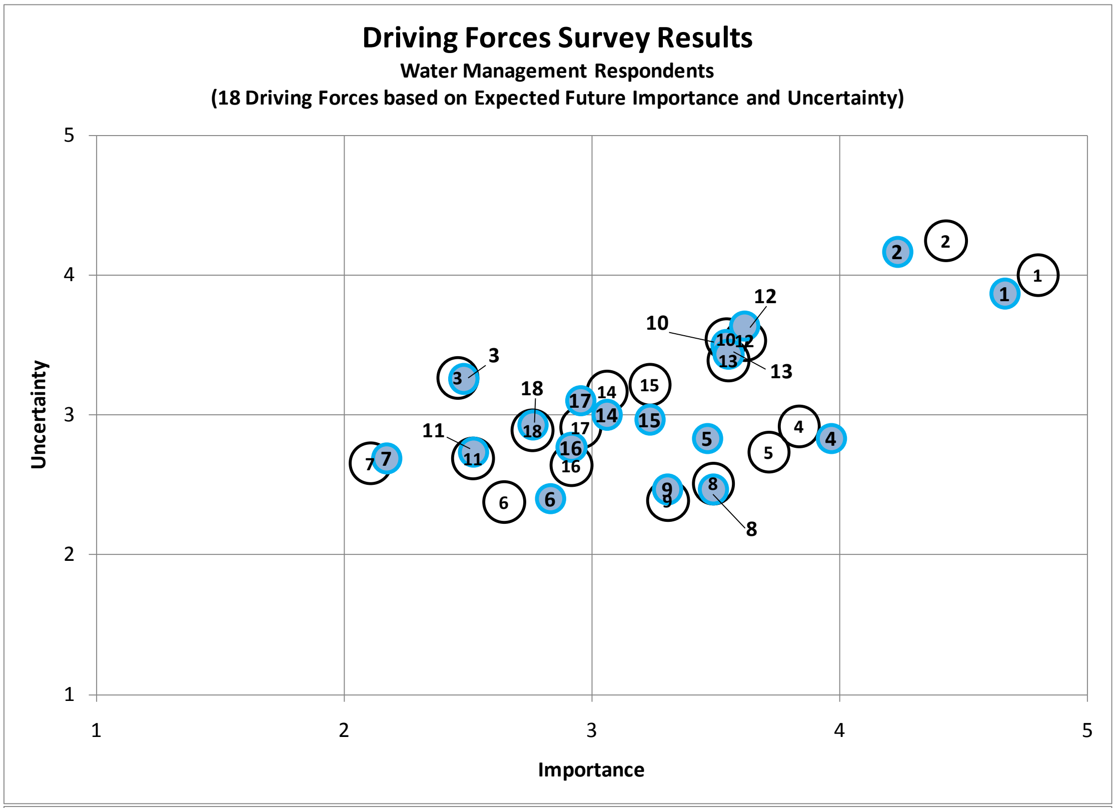
FIGURE A-5
Plot of Mean Results from Driving Forces Survey

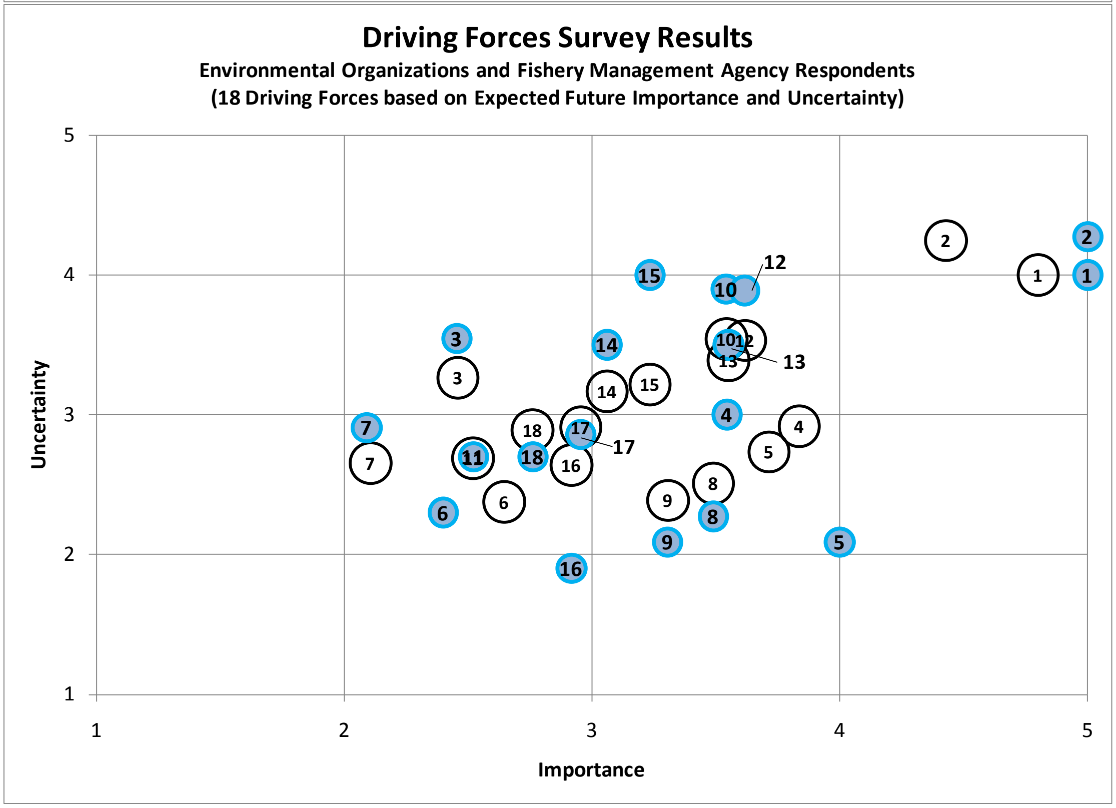


Because of the differences in the number of respondents among groups, results based on particular respondent groups were evaluated. Figure A-6 represents the results from water management entity respondents (top) and the results from the conservation organizations and fishery management entities (bottom). In this figure, the hollow circles represent the ranking based on all responses, and the shaded circles represent the responses from the particular respondent group.

While the sample sizes were small when partitioning in this fashion, there was a strong commonality of the results among these groups. For example, both respondent groups rated the streamflow variability (No. 1) and climate change (No. 2) driving forces as the highest, despite differences in absolute scores. Similarly, water needs for energy generation (No. 12) and flow-dependent needs for ESA-listed species (No. 13) were rated highly important and highly uncertain by both groups.

FIGURE A-6
Plot of Mean Results from Driving Forces Survey Water Management Respondents (top, 31 respondents), and Environmental Organizations and Fishery Management Agencies (bottom, 12 respondents)



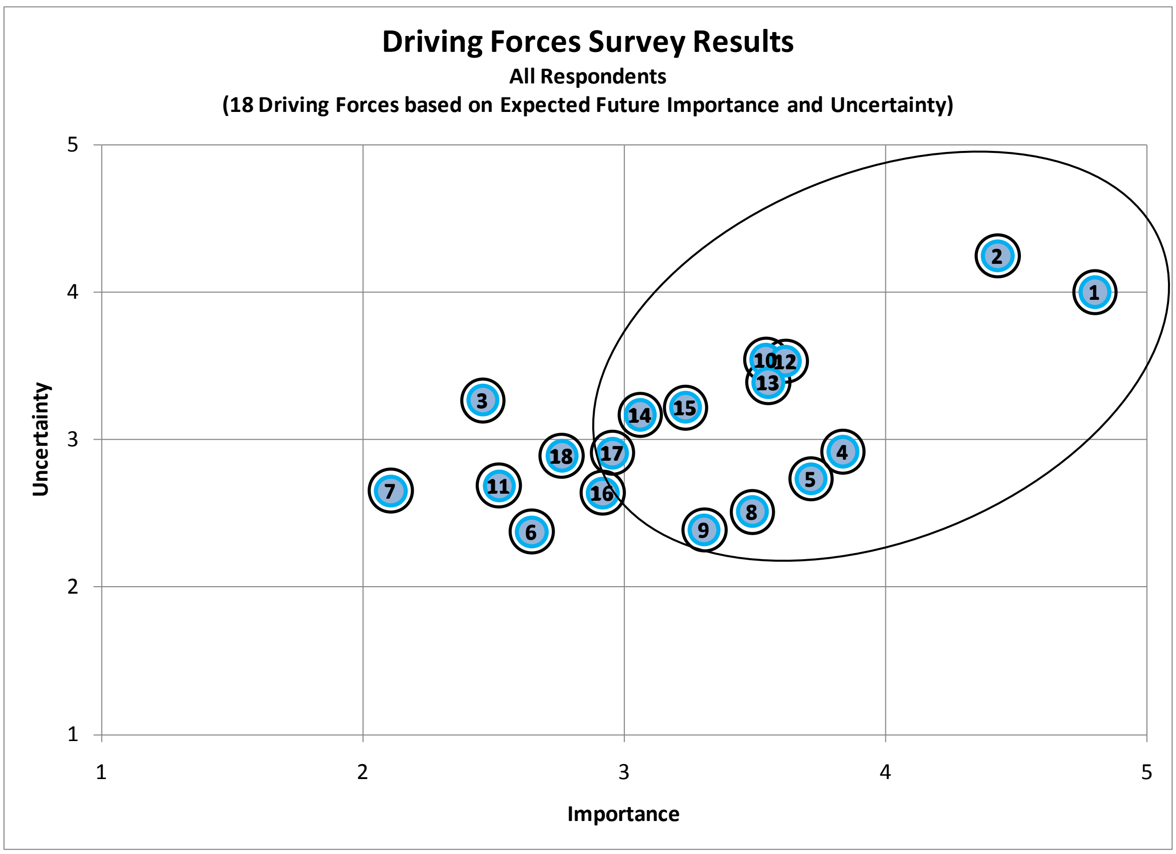


4.4 Identify Critical Uncertainties

Consideration of the relative rankings based on the survey responses led to identification of the critical uncertainties, as shown in the oval in figure A-7. The driving forces that were obviously located in the upper right in the figure were selected as critical uncertainties. For the driving forces near the middle of the graph, judgment and expertise were used to decide whether they should be considered as critical uncertainties.

The initial list of critical uncertainties was checked to see if the results would have been different based on responses of individual respondent groups. Although there were some differences in terms of the relative magnitude of the ratings, it was concluded that the driving forces representing the critical uncertainties would not be different based on subsets of the survey responses. In general, the decision was made to be more inclusive, and the oval was expanded to include several of the driving forces in the middle range.

FIGURE A-7
Plot of Mean Results from Driving Forces Survey and Selected Critical Uncertainties



4.5 Associate Critical Uncertainties with Water Supply and Water Demand

Water supply and water demand are the key factors affecting the future reliability of the Colorado River system. Although critical uncertainties may affect both supply and demand, each critical uncertainty was associated with the factor thought to be most affected. For critical uncertainties that have significant impact to both supply and demand, adjustments to parameters affecting both water supply and water demand were made.

The critical uncertainties were first grouped by the broader categories of driving forces. Then each driving force category was aligned with either water supply or water demand, depending on its anticipated area of greatest influence. The resulting association of critical uncertainties is shown in table A-4. The alignment of driving forces into water supply or water demand was performed to provide focus to the evaluation of the driving force, but the subsequent quantification of scenarios considered important linkages across water supply and water demand. For example, although changes in climate variability and trends will affect water demand (primarily through increased evapotranspiration due to increase in temperature), the potential influence is considered greater on water supply. For scenarios that explicitly included climate change, the associated demands were adjusted based on temperature-related effects on evapotranspiration (see *Technical Report C – Water Demand Assessment*).

TABLE A-4
Association of Critical Uncertainties with Key Factors in System Reliability

Key Basin Study Driving Forces Identified in Survey	General Driving Force Category	Key Factor In System Reliability Most Affected
Changes in streamflow variability and trends [No. 1] Changes in climate variability and trends (e.g., temperature, precipitation, etc.) [No. 2]	Natural Systems (Hydroclimate)	Water Supply
Changes in population and distribution [No. 4] Changes in agricultural land use (e.g., irrigated agricultural areas, crop mixes, etc.) [No. 5]	Demographics and Land Use	Water Demand
Changes in agricultural water use efficiency [No. 8] Changes in municipal and industrial water use efficiency [No. 9] Changes in water needs for energy generation (e.g., solar, oil shale, thermal, nuclear, etc.) [No. 12]	Technology and Economics	Water Demand
Changes in institutional and regulatory conditions (e.g., laws, regulations, etc.) [No. 10] Changes in flow-dependent ecosystem needs for ESA-listed species [No. 13] Changes in other flow-dependent ecosystem needs [No. 14] Changes in social values affecting water use [No. 15] Changes in water availability due to tribal water use and settlement of tribal water rights claims [No. 17]	Social and Governance	Water Demand

4.6 Develop Water Supply and Water Demand Scenarios

After determining the associations of the critical uncertainties to the key factors of water supply and demand, additional stakeholder and subject matter expertise was sought to complete the scenario development process through the Water Supply and Water Demand Sub-Teams. Each sub-team had different requirements and therefore followed different steps, as shown in figure A-4. These steps are discussed in *Technical Report B – Water Supply Assessment* and *Technical Report C – Water Demand Assessment*, respectively.

The following scenarios were considered in the Study:

Water Supply Scenarios

- Observed Resampled
- Paleo Resampled
- Paleo Conditioned
- Downscaled General Circulation
- Model (GCM) Projected

Water Demand Scenarios

- Current Projected (A)
- Slow Growth (B)
- Rapid Growth (C1 and C2)
- Enhanced Environment (D1 and D2)

The themes associated with each scenario are described below.

The water supply scenarios were focused around the key driving forces in the "natural systems" category. These driving forces relate primarily to streamflow variability and trends, and climate variability and trends. Reclamation has conducted research and development relating to the uncertainty of future hydrologic conditions, and these previous efforts were incorporated to the extent possible. The water supply scenarios used significant information from the observed record of streamflow, reconstructions of streamflow from tree-ring records, and projections of future hydroclimate conditions using downscaled global climate model results. The themes associated with the water supply scenarios are:

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

The assumptions, methods, and results for each of these water supply scenarios are discussed in detail in *Technical Report B – Water Supply Assessment*.

The water demand scenarios were focused on the driving forces related to the general driving force categories, of "demographics and land use," "technology and economics," and "social and governance." The Water Demand Sub-Team identified the parameters that most significantly influence each critical uncertainty within the demand-focused categories. The range of parameter characteristics and the logical combinations of those characteristics were explored by the Water Demand Sub-Team, resulting in the following themes:

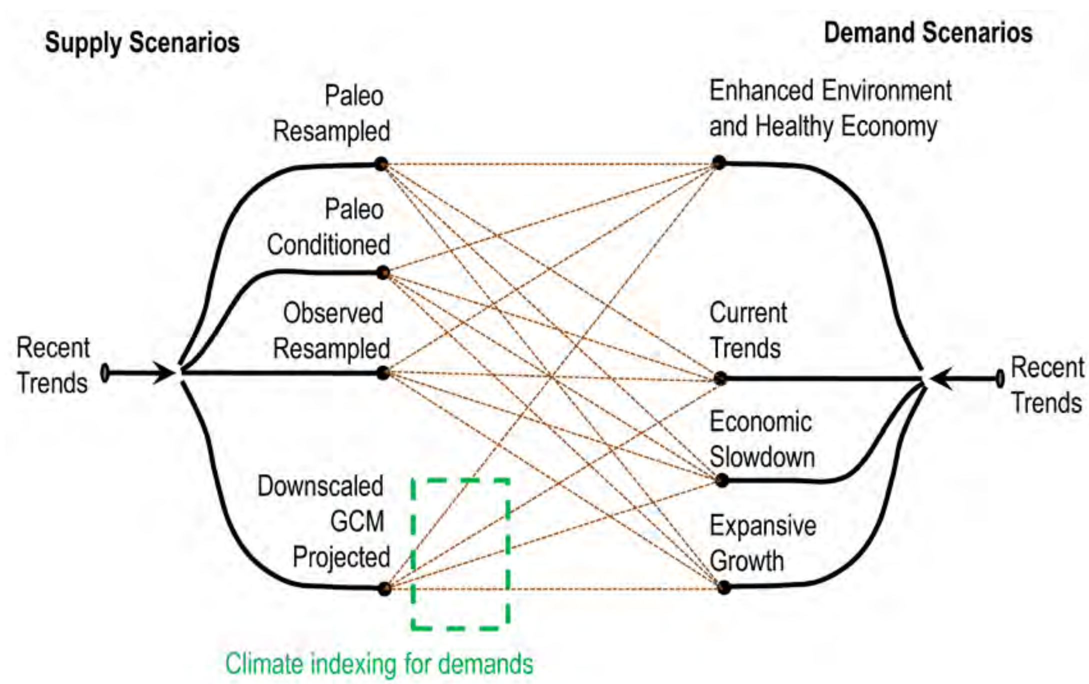
- **Current Projected (A):** Growth, development patterns, and institutions continue along recent trends
- **Slow Growth (B)**: Slow growth with emphasis on economic efficiency
- **Rapid Growth (C1 and C2)**: Economic resurgence (population and energy) and current preferences toward human and environmental values
- **Enhanced Environment (D1 and D2)**: Expanded environmental awareness and stewardship with growing economy

The assumptions, methods, and storylines for each of the water demand scenarios are discussed in detail in *Technical Report C – Water Demand Assessment*.

5.0 Conclusions

To assess the future reliability of the Colorado River system, the water supply and water demand scenarios were combined to yield scenarios for both supply and demand, as depicted in figure A-8 and described in detail in *Technical Report A – Water Supply Assessment* and *Technical Report B – Water Demand Assessment*. Each water supply scenario, relating primarily to the driving forces of streamflow and climate variability and trends, was combined with each water demand scenario, relating to "demographics and land use," "technology and economics," and "social and governance" driving forces to capture a more-complete description of the range of future uncertainty influencing the Colorado River system. All combinations of water supply and water demand scenarios were used to assess system reliability for a sufficiently broad range of plausible futures.

FIGURE A-8
Illustration of Combined Water Supply and Water Demand Scenarios



6.0 References

Alcamo, J. and Gallopin, G. 2009. *United Nations World Water Assessment Programme, Building a 2nd Generation of World Water Scenarios*.

Mara, R. and T. Thomure. 2009. "Scenario Planning: Making Strategic Decisions in Uncertain Times." *Southwest Hydrology*. May/June.

Timpe, C. and M.J.J. Scheepers. 2003. *SUSTELNET: A Look into the Future: Scenarios for Distributed Generation in Europe*.

Water Utility Climate Alliance. 2010. *Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning*.

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 was constrained by funding, timing, and technological and other limitations, and in some cases presented 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 developed and incorporated assumptions to further complete the Study. Where possible, a range of assumptions was typically 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.

Appendix B1
Water Supply Sub-Team Members

Appendix B1 — Water Supply Sub-Team Members

The information presented in *Technical Report B – Water Supply Assessment* is the outcome of a collaborative process involving representatives of numerous organizations.

A list of Water Supply Sub-Team members and their affiliations is presented below.

- Carly Jerla, Bureau of Reclamation
- Chuck Cullom, Central Arizona Project
- Tapash Das, CH2M HILL
- Armin Munévar, CH2M HILL
- Jerry Zimmerman, Colorado River Board of California
- Robert Kirk, Navajo Nation
- John Whipple, New Mexico Interstate Stream Commission
- Mike Roberts, The Nature Conservancy
- John Gerstle, Trout Unlimited
- Steve Cullinan, U.S. Fish and Wildlife Service
- Robert King, Utah Division of Natural Resources

Additional support in the form of supplemental analysis, review, and information was provided by those listed below.

- Ben Harding, AMEC Earth & Environmental
- Ken Nowak, Bureau of Reclamation
- Jim Prairie, Bureau of Reclamation
- Levi Brekke, Bureau of Reclamation’s Technical Service Center
- Subhrendu Gangopadhyay, Bureau of Reclamation’s Technical Service Center
- Tom Pruitt, Bureau of Reclamation’s Technical Service Center
- Joe Barsugli, University of Colorado and the National Oceanic and Atmospheric Administration

Appendix B2
Supplemental Water Supply Data and Methods

Appendix B2 — Supplemental Water Supply Data and Methods

This appendix provides supplemental information related to the water supply data and methods discussed in the Technical Report. As discussed in the Technical Report, the assessment of historical and future supply conditions focused on four main groups of water supply indicators: climate, hydrologic processes, climate teleconnections, and streamflow. Although the primary indicator of water supply in the Colorado River Basin (Basin) is streamflow, a fundamental understanding of the processes that influence the quantity, location, and timing of streamflow is beneficial. Additional detail on the methods used to assess these indicators for water supply is supplied in this appendix.

Table B2-1 summarizes the water supply indicators evaluated as part of the Water Supply Assessment. In addition, the table provides the relevance of the particular parameter for the Colorado River Basin Water Supply and Demand Study (Study), temporal and spatial scales considered, and analysis methods. Table B2-2 summarizes the data sources considered in the evaluation of each of the water supply indicators. The subsequent sections provide further detail on the data and methods under each of the four water supply indicator groups.

TABLE B2-1
Summary of the Water Supply Indicators for the Water Supply Assessment

Water Supply Indicator	Relevance	Temporal Scale	Spatial Scale	Method of Analysis	Method of Display
CLIMATE					
Temperature	Identification of trends in climate patterns	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Statistical analysis of trends and variability	Spatial analysis and visualization
Precipitation	Identification of trends in climate patterns	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Statistical analysis of trends and variability	Spatial analysis and visualization
HYDROLOGIC PROCESSES					
Runoff	Identification of changes in runoff processes; identification of "productive" watersheds	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Calculated as unit runoff; statistics to be generated	Spatial analysis and visualization
Evapotrans-piration (ET)	Identification of changes in natural losses; identification of "water stressed" watersheds	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Calculated as unit actual ET; statistics to be generated	Spatial analysis and visualization

TABLE B2-1
Summary of the Water Supply Indicators for the Water Supply Assessment

Water Supply Indicator	Relevance	Temporal Scale	Spatial Scale	Method of Analysis	Method of Display
Snowpack Accumulation and Snowmelt	Identification of spatial changes in snowpack development and timing of melt	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Calculated as unit snow water equivalent (SWE); peak and timing	Spatial analysis and visualization
Soil Moisture	Identification of causes of drought and severe drying conditions; identification of watersheds most impacted	Monthly, Seasonal, Annual, Decadal	Grid cell, Select Watersheds, and Basin-wide	Calculated as percentage of maximum	Spatial analysis and visualization
CLIMATE TELECONNECTIONS					
El Niño – Southern Oscillation (ENSO)	Identify changes in teleconnections and influence on regional climate; identify relationship between long-term and shorter-term climate indices	Season, Annual, Decadal	Global/ Regional	Statistical analysis of correlation between indicator and streamflow	Correlation plots and statistics
Pacific Decadal Oscillation (PDO)	Identify changes in teleconnections and influence on regional climate; identify relationship between long-term and shorter-term climate indices	Annual, Decadal	Global/ Regional	Statistical analysis of correlation between indicator and streamflow	Correlation plots and statistics
Atlantic Multi-decadal Oscillation (AMO)	Identify changes in teleconnections and influence on regional climate; identify relationship between long-term and shorter-term climate indices	Annual, Decadal	Global/ Regional	Qualitative discussion	Qualitative discussion
STREAMFLOW					
Intervening and Total Natural Flows at 29 Basin Locations	Identification of changes in streamflow trends and variability	Monthly; Annual; 1-, 3-, 5-, 10-year; and multi-decadal	Accumulated Flow at Point	Statistical analysis of trends and variability; drought and surplus statistics	Table and box-whisker of statistics, Basin-scale maps

TABLE B2-2
Sources of Data Used for the Water Supply Assessment

Parameter	Description	Data Source
CLIMATE INDICATORS		
Historical Temperature and Precipitation	Historical gridded temperature and precipitation at 1/8th-degree resolution for the period of 1950–1999. Extension through 2005 was not documented.	Maurer et al., 2002 (http://www.engr.scu.edu/~emaurer/ data.shtml)
Future Temperature and Precipitation Projections	A total of 112 future monthly temperature and precipitation projections based on Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) emission scenarios, subsequently bias corrected, and statistically downscaled to 1/8th-degree resolution for the period of 1950–2099.	Maurer et al., 2007 (http://gdo-dcp.ucllnl.org downscaled_cmip3_projections/)
HYDROLOGIC PROCESS INDICATORS		
ET, Runoff, SWE, Soil Moisture	Variable Infiltration Capacity (VIC)-simulated hydrologic fluxes and grid cell storage terms driven by observed climatology (1950–2005) and 112 future climate projections (1950–2099).	Bureau of Reclamation (Reclamation), 2011
Snowpack	Point snow water equivalent from late 1970s to present from the snow-telemetry (SNOTEL) network.	National Resources Conservation Service, 2011 (http://www.wcc.nrcs.usda.gov/snow/)
TELECONNECTION INDICATORS		
ENSO	Monthly Southern Oscillation Index (SOI) for January 1866 through March 2010.	University of East Anglia Climatic Research Unit , 2010 (http://www.cru.uea.ac.uk/cru/data/soi/)
PDO	Monthly PDO indices for January 1900 through January 2010.	Joint Institute for the Study of the Atmosphere and Ocean, 2010 (http://jisao.washington.edu/pdo/)
STREAMFLOW INDICATORS		
Observed Streamflow used in the Observed Resampled Scenario	Natural streamflow for the period of 1906–2007 for the 29 streamflow locations commonly used for Reclamation planning.	Prairie and Callejo, 2005; Reclamation, 2010
Paleo Reconstructed Streamflow used in the Paleo Resampled Scenario	Reconstructed natural streamflows for the period 762–2005 at 29 locations derived from ecologically contrasting tree-ring sites in the southern Colorado Plateau during the past 2 millennia.	Reclamation, 2010; Meko et al., 2007
Paleo Conditioned Streamflow used in the Paleo Conditioned Scenario	Blended paleo streamflow states with observed streamflow magnitudes at 29 locations.	Prairie et al., 2008
Future Streamflow Projections used in the Downscaled General Circulation Model (GCM) Projected Scenario	VIC-simulated runoff and routed streamflow at 29 locations driven by 112 future climate projections for the period 1950–2099.	Reclamation, 2011

1.0 Climate

1.1 Historical Climate

Gridded observed climate data for the period from 1950 to 1999, as developed by Maurer et al. (2002), were downloaded via the Internet from Santa Clara University (http://www.engr.scu.edu/~emaurer/data.shtml). The data are stored in network common data format (netCDF) at 1/8th-degree resolution and contain daily temperature (minimum and maximum), precipitation, and wind speed values for the contiguous United States. Subsequent to the Maurer et al. (2002) data, the gridded dataset was extended to 2005 using identical methods. The temperature and precipitation data were processed into monthly average temperature and monthly total precipitation to facilitate comparisons. The monthly, seasonal, and annual statistics were computed for each parameter and for each grid cell for the period 1971 to 2000 to facilitate comparisons to projected future conditions. This 1971 to 2000 historical base period was selected as the most current 30-year climatological period at the time of the Study, as described by the National Oceanic and Atmospheric Administration (NOAA) (2010), and was used as the basis for comparing to future climate projections[1].

1.2 Projections of Future Climate

Future climate change projections are made primarily on the basis of General Circulation Model (GCM) simulations under a range of future emission scenarios. A total of 112 future climate projections used in the IPCC Fourth Assessment Report, subsequently transformed to a local scale through bias correction and spatial downscaling (BCSD), were obtained from the Lawrence Livermore National Laboratory under the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3). This archive contains climate projections generated from 16 different GCMs developed by national climate centers and for *Special Report on Emissions Scenarios* emission scenarios A2, A1B, and B1. These projections have been bias corrected and spatially downscaled to 1/8th-degree (~12-kilometer) resolution over the contiguous United States through methods described in detail in Wood et al. (2002; 2004) and Maurer (2007).

1.2.1 Emission Scenarios

In 2000, IPCC published the SRES scenarios that described a family of six emission scenarios to condition GCMs (IPCC, 2000). The emissions scenarios are defined by alternative future development pathways, covering a wide range of demographic, economic, and technological driving forces and resulting greenhouse gas (GHG) emissions. The GHG emissions associated with each scenario are shown in figure B2-1.

[1] A new 30-year historical base period (1981 to 2010) was issued by NOAA on July 1, 2011.

FIGURE B2-1
Scenarios for GHG Emissions from 2000–2100 in the Absence of Additional Climate Policies
Units on the y-axis are billon tons of total annual emissions in equivalent carbon dioxide units.

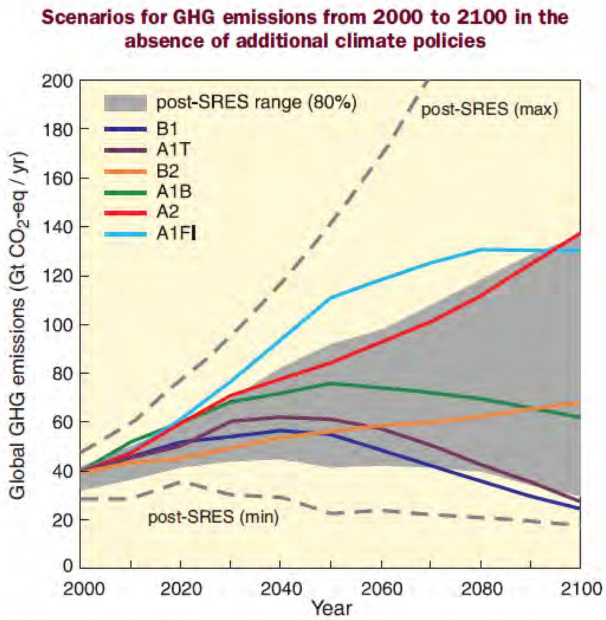


Figure 3.1. *Global GHG emissions (in GtCO$_2$-eq per year) in the absence of additional climate policies: six illustrative SRES marker scenarios (coloured lines) and 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include CO$_2$, CH$_4$, N$_2$O and F-gases. {WGIII 1.3, 3.2, Figure SPM.4}*

Source: (IPCC, 2007)

Of the six emission scenarios included in the IPCC Fourth Assessment Report (IPCC, 2007), three were selected to drive the CMIP3 multi-model dataset—A2 (high), A1B (medium), and B1 (low). The A2 scenario is representative of high population growth, slow economic development, and slow technological change. It is characterized by a continuously increasing rate of GHG emissions and features the highest annual emissions rates of any scenario by the end of the 21st Century. The A1B scenario features a global population that peaks mid-century and rapid introduction of new and more-efficient technologies balanced across both fossil- and non-fossil-intensive energy sources. As a result, GHG emissions in the A1B scenario peak around mid-century. Lastly, the B1 scenario describes a world with rapid changes in economic structures toward a service and information economy. GHG emission rates in this scenario peak prior to mid-century and are generally the lowest of the scenarios. The best estimates of global temperature change during the 21st Century for each of the A2, A1B, and B1 scenarios are 3.4, 2.8, and 1.8 degrees Celsius (°C), respectively[2] (IPCC, 2007) as shown in Figure B2-2.

[2] Temperature change reflects the difference between the global average in the 2090 to 2099 period relative to the global average in the 1980 to 1999 period.

FIGURE B2-2
Projections of Surface Temperatures for the Selected GHG Emissions Scenarios from 2000–2100

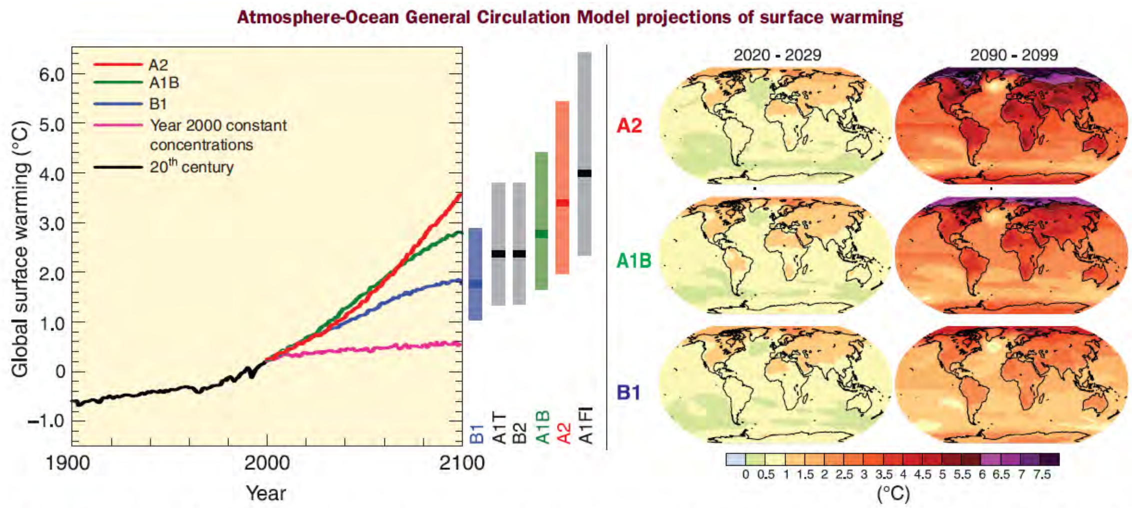


Figure 3.2. ***Left panel:*** *Solid lines are multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. The orange line is for the experiment where concentrations were held constant at year 2000 values. The bars in the middle of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999. The assessment of the best estimate and likely ranges in the bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.* ***Right panels:*** *Projected surface temperature changes for the early and late 21st century relative to the period 1980-1999. The panels show the multi-AOGCM average projections for the A2 (top), A1B (middle) and B1 (bottom) SRES scenarios averaged over decades 2020-2029 (left) and 2090-2099 (right). {WGI 10.4, 10.8, Figures 10.28, 10.29, SPM}*

Source: (IPCC, 2007)

1.2.2 General Circulation Models

The CMIP3 multi-model dataset consists of 112 unique climate projections. Sixteen GCMs were coupled with the three emissions scenarios described previously to generate these projections. Many of the GCMs were simulated multiple times for the same emission scenario due to differences in starting climate system state or initial conditions, so the number of available projections is greater than simply the product of GCMs and emission scenarios. Table B2-3 summarizes the GCMs, initial conditions (specified by the run numbers in the A2, A1B, and B1 columns), and emissions scenario combinations (A2, A1B, and B1) featured in the CMIP3 dataset. Initial conditions (initial atmosphere and ocean conditions used in a GCM simulation) for the 21st Century are defined by the 20th Century “control” simulation. A description of the 20th Century “control” simulations corresponding to each GCM simulation in table B2-3 can be found at http://www-pcmdi.llnl.gov/ipcc/standard_output.html#Experiments.

TABLE B2-3
WCRP CMIP3 Multi-Model Dataset GCMs, Initial Conditions, and Emissions Scenarios

Modeling Group, Country	WCRP CMIP3 I.D.	A2	A1B	B1	Primary Reference
Bjerknes Center for Climate Research, Norway	BCCR-BCM2.0	1	1	1	Furevik et al., 2003
Canadian Center for Climate Modeling and Analysis, Canada	CGCM3.1 (T47)	1…5	1…5	1…5	Flato and Boer, 2001
Meteo-France/Center National de Recherches Meteorologiques, France	CNRM-CM3	1	1	1	Salas-Melia et al., 2005
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	1	1	1	Gordon et al., 2000
U.S. Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, United States	GFDL-CM2.0	1	1	1	Delworth et al., 2006
U.S. Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, United States	GFDL-CM2.1	1	1	1	Delworth et al., 2006
National Aeronautics and Space Administration/Goddard Institute for Space Studies, United States	GISS-ER	1	2, 4	1	Russell et al., 2000
Institute for Numerical Mathematics, Russia	INM-CM3.0	1	1	1	Diansky and Volodin, 2002
Institut Pierre Simon Laplace, France	IPSL-CM4	1	1	1	Institut Pierre Simon Laplace, 2005
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan	MIROC3.2 (medres)	1…3	1…3	1…3	K-1 Model Developers, 2004
Meteorological Institute of the University of Bonn, Germany and Institute of Korea Meteorological Administration, Korea	ECHO-G	1…3	1…3	1…3	Legutke and Voss, 1999
Max Planck Institute for Meteorology, Germany	ECHAM5/MPI-OM	1…3	1…3	1…3	Jungclaus et al., 2006
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	1…5	1…5	1…5	Yukimoto et al., 2001
National Center for Atmospheric Research, United States	CCSM3	1…4	1…3, 5…7	1…7	Collins et al., 2006
National Center for Atmospheric Research, United States	PCM	1…4	1…4	2…3	Washington et al., 2000
Hadley Center for Climate Prediction and Research/Met Office, United Kingdom	UKMO-HadCM3	1	1	1	Gordon et al., 2000
Total Number of Climate Projections		**36**	**39**	**37**	

Source: (Maurer et al., 2007)

1.2.3 Bias Correction and Spatial Downscaling

The CMIP3 climate projections have undergone BCSD to 1/8th-degree (~12-kilometer) resolution through methods described in detail in Wood et al. (2002; 2004) and Maurer (2007). The purpose of this bias correction is to adjust a given climate projection for inconsistencies between the simulated historical climate data and observed historical climate data, which are the result of GCM bias. In the BCSD approach, projections are bias corrected using a quantile mapping technique at 2-degree (~200-kilometer) spatial resolution. Following bias correction, the adjusted climate projection data are statistically consistent on a monthly basis with the observed climate data for the historical overlap period, which was 1950 to 1999 in the Study. Beyond the historical overlap period (2000 to 2099), the adjusted climate projection data reflect the same relative changes in mean, variance, and other statistics between the projected (2000 to 2099) and historical periods (1950 to 1999) as were present in the unadjusted dataset, but the adjusted climate projection data are mapped onto the observed dataset variance. This methodology assumes that the GCM biases have the same structure during the 20th and 21st Century simulations.

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

1.2.4 Weather Generation (Temporal Disaggregation)

The resulting BCSD climate projections provide a representation of future monthly temperature and precipitation through 2099. However, to be useful for hydrologic modeling, this information is required on a daily temporal scale. The monthly downscaled data were temporally disaggregated to a daily temporal scale to create realistic weather patterns using the sampling methods described in Wood et al. (2002) with extensions of this approach as applied by Salathé (2005) and Mote and Salathé (2010). To generate daily values, for each month in the simulation a month is randomly selected from the historic record for the same month (e.g., for the month of January, a January from the 1950 to 1999 period is selected). The daily precipitation and temperature from the historic record are then adjusted (rescaled precipitation and shifted temperature) such that the monthly average matches the simulated monthly value. The same historic month is used throughout the domain to preserve plausible spatial structure to daily storms (Mote and Salathé, 2010). The results of the temporal disaggregation are daily weather sequences that preserve the monthly values from the downscaled climate projections. Some uncertainties can be introduced depending on the method employed to produce the daily data from the monthly climate values. A comparative analysis of two available methods to generate daily weather patterns for the Study favored the use of the method employed by Salathé (2005) and incorporated in the SECURE Report (Reclamation, 2011) to produce the daily downscaled data. Additional detail of the comparative analysis of two daily weather generation (temporal disaggregation) methods is presented in appendix B3 under Comparison of Daily Weather Generation (Temporal Disaggregation) Methods.

2.0 Hydrologic Processes

The primary sources for hydrologic process data are derived from the VIC-simulated conditions driven by either observed historical climatology (1950 to 2005) or projected climate (1950 to 2099). VIC simulates all major moisture fluxes at the grid cell using physically based methods. These moisture fluxes are not generally measured at the spatial resolution necessary for Basin assessments; thus the VIC-derived patterns are considered the most suitable source. For example, although station-specific SWE, precipitation, and temperature are available from the National Resources Conservation Service SNOTEL network at 800 stations in 11 western states and Alaska (http://www.wcc.nrcs.usda.gov/snow/), the spatial representativeness of the SNOTEL data is uncertain (Daly et al., 2000). In preliminary results, Molotch et al. (2001) showed that SWE can begin to vary significantly beyond 500 meters from a SNOTEL site, due to terrain impacts on snow ablation, as well as small-scale depositional variations. A variety of methods have been used to distribute point measurements to spatial grids. The methods used are complex and beyond the scope of the Study; therefore, site-specific SNOTEL data were not processed to independently validate the SWE fields derived from the VIC model for the Study. However, Mote et al. (2008) found correlation of better than 0.75 between VIC-simulated SWE and measured SWE for the Rockies. Other parameters, such as ET and soil moisture, are not routinely measured, nor are they measured at scales that permit validation with the VIC-simulated fields. Thus, the use of VIC-simulated historical fluxes enables a consistent comparison of change when considering simulated fluxes under future climate.

Both the climate and hydrologic data from VIC simulations are stored in formatted text files known as “flux files.” One flux file is produced for every grid cell of the model domain, and each file contains values for the specified parameters at every time step of the simulation. Gridded climate and hydrologic parameter data generated by the VIC model for the historical and projected periods were converted from daily to monthly values and stored in a specialized format (netCDF). This data conversion allows for statistical and spatial analysis of the data and enables a better understanding of the primary factors, both climatological and hydrological, that drive projected changes in streamflows relative to historical conditions. In addition to the primary VIC outputs of air temperature, precipitation, ET, runoff, and baseflow, total runoff (sum of baseflow and runoff) and runoff efficiency were computed at each grid cell and added to the netCDF files. Runoff efficiency is defined as the fraction of total runoff to the total precipitation. The complete list of hydroclimatic variables compiled is included in table B2-4.

One netCDF file was produced for each climate projection and for the historical observed data, for a total of 113 netCDF files. As with the climate data, monthly, seasonal, and annual statistics were derived for the hydrologic process information for the historical period 1971 to 2000 and three future 30-year climatological periods: 2011 to 2040, 2041 to 2070, and 2066 to 2095. The historical period 1971 to 2000 was selected as the reference climate because it was the most current 30-year climatological period described by NOAA (2010) at the time the Study was initiated. Representative statistics were generated on monthly, seasonal, and annual bases. In this analysis, the seasons are defined as follows: Fall: October, November, and December; Winter: January, February, and March; Spring: April, May, and June; and Summer: July, August, and September.

TABLE B2-4
Climate and Hydrologic Parameters

VIC Parameter	Units
Average air temperature	°C
Precipitation	millimeters (mm)
ET	mm
Runoff (surface)	mm
Baseflow (subsurface)	mm
Total runoff	mm
Soil moisture (in each of three soil layers)	mm
Soil moisture fraction	percent
SWE	mm
Runoff efficiency (total runoff/total precipitation)	fraction

The statistical analysis was conducted on both grid cell and watershed bases. The results of the grid cell analysis produce the most informative map graphics and clearly show spatial variation at the greatest resolution possible. At this spatial scale, the statistics for each grid cell are developed independently. The resulting statistics are stored in netCDF files. Monthly time series data were extracted from these files to characterize patterns of change in hydrologic parameters.

Finally, "change metrics" are generated for each parameter, in which the difference between future period statistics and historical period statistics are calculated on both absolute and percent change bases. These results are again stored in netCDF files, with two files generated for each future period—one for grid cell data and one for watershed data. The format of these files is identical to those containing the results of the statistical analysis.

3.0 Climate Teleconnections

During the past 30 years, the understanding of the climatic importance of the oceans, particularly ocean temperature, has steadily improved (U.S. Department of Interior, 2004). Initial research focused on the distant effects of the recurrent warming of the equatorial Pacific Ocean referred to as El Niño, which South American fishermen have long known to have an adverse effect on the coastal fisheries in Peru. El Niño is the warm phase of the sea-surface temperature component of a coupled ocean-atmosphere process, ENSO, which spans the equatorial Pacific Ocean. The atmospheric component, the Southern Oscillation, refers to a "seesaw" effect in sea-level pressure between the tropical Pacific and Indian Oceans. Reduced sea-level pressure in the Pacific Ocean, combined with increased sea-level pressure in the Indian Ocean, leads to a weakening in the trade winds over the eastern Pacific. This weakening enables warm water from the central equatorial Pacific to spread eastward and southward along the west coast of South America, creating the classic El Niño condition. Conversely, and about as frequently, the sea-level pressure in the Pacific Ocean increases while pressure in the Indian Ocean decreases, which causes trade winds to intensify over the eastern Pacific. When this occurs, equatorial upwelling of deep, cold water, as well as cold water from the West Coast of South America, are pulled northward and westward from the coast into the eastern and central Pacific, producing La Niña. Thus, El Niño and La Niña are, respectively, the warm and cold phases of the coupled ENSO system.

ENSO events typically last from 6 to 18 months and, therefore, are the single most important factor affecting inter-annual climatic variability on a global scale (Diaz and Kiladis, 1992). ENSO has been linked to the occurrence of flooding in the Lower Basin (Webb and Betancourt, 1992) and to both floods and droughts across the western United States (Cayan et al., 1999). Warm winter storms have been enhanced during El Niño, causing above-average runoff and floods in the Southwest, such as during 1982 and 1983. However, not all El Niño events lead to increased runoff in the Southwest. For example, during the 2002 to 2003 warm episode, runoff was below average in the Basin. Similarly, La Niña is frequently, though not always, associated with below-average flow in the Colorado River. As a result, although ENSO exerts a strong influence in modulating wet versus dry conditions in many parts of the United States, the effect is not always the same in any given region. Some condition other than ENSO must also be influencing weather and climate patterns affecting the Colorado River.

In the mid-1990s, scientists identified another ocean temperature pattern, this one occurring in the extratropical Pacific Ocean north of 20 ºN (Mantua and Hare, 2002), the PDO. The PDO varies or oscillates on a decadal scale of 30 to 50 years for the total cycle; that is, much of the North Pacific Ocean is predominantly, though not uniformly, warm (or cool) for periods of about 15 to 25 years. During the 20th Century, the PDO exhibited several phases−warmer along coastal southeastern Alaska from 1923 to 1943 and again from 1976 to 1998, and cooler from 1944 to 1975. Since 1999, the PDO has exhibited higher-frequency fluctuations, varying from cool (1999 to 2001) to warm (2002 to 2004). Currently, the causes of the variations in the PDO are unknown and its potential predictability is uncertain. Recent research indicates that the PDO phase may be associated with decadal-length periods of above- and below-average precipitation and streamflow in the Basin (Hidalgo, 2004) but, as with ENSO, such associations are not always consistent.

Climate teleconnections were first analyzed by selecting indices that could have potential influence in streamflow changes for the Basin. Published research (Redmond and Koch, 1991; Webb and Betancourt, 1992; Cayan et al.; 1999; Mo et al., 2009; and others) indicates that the strongest correlations with Basin flows were observed with the PDO and ENSO indices. For ENSO, data were collected for both the ocean component (sea surface temperature anomalies) and the atmospheric component. The two components are highly correlated and combined describe ENSO. The SOI, the atmospheric component, was the primary dataset used in the Study due to the longer availability of information. Therefore, the quantitative teleconnections analysis was based on the PDO index and the SOI. Only a qualitative discussion of the AMO is included in the Technical Report.

Annual averages of the PDO on a water-year basis were calculated and compared with the same water year annual flows. Annual average values for the SOI were computed, using different annual windows. The average SOI index presented in the Study refers to the June to November period, which was identified as a strong indicator of ENSO events (Redmond and Koch, 1991). Once the SOI averages were computed, ENSO events were determined by years when the averaged SOI was below -1 (classified as an El Niño year) or above 1 (classified as a La Niña year). A warm PDO was defined as a PDO value greater than or equal to 0.0, and a cold PDO was a PDO value less than 0.0. AMO research by Mo et al. (2009) indicates that the direct influence of the AMO on drought is small. The major influence of the AMO is to modulate the impact of ENSO on drought. The influence is large when the sea surface temperature anomalies in the tropical Pacific and in the North Atlantic are opposite in phase. A cold (warm) event in a positive (negative) AMO phase amplifies the impact of the cold (warm) ENSO on drought. The ENSO influence on drought is much weaker when the sea surface temperature anomalies in the tropical Pacific and in the North Atlantic are in phase. Because the AMO cycle is approximately 70 years, AMO research is constrained by the observed data record of approximately 150 years. AMO research continues in this area using indirect observations of tree rings and sedimentary layers.

There are also other climate teleconnections that appear to influence the characteristics of seasonal precipitation (e.g., Madden-Julian Oscillation and Arctic Oscillation) (Becker et al., 2011; Bond and Vecchi, 2003; Hu and Feng, 2010). However, the understanding of the influence of these teleconnections on the Colorado River precipitation, and their usefulness as an indicator, is still evolving.

4.0 Streamflow

Streamflow was analyzed through the use of two historical data sets (observed period and a longer paleo-reconstructed period) and projections of future streamflow based on climate models. Using information from the recent past, more distant past, and projections of the future enabled a robust assessment of plausible future conditions.

Two historical streamflow data sets—the observed record spanning the period 1906 to 2007 and the paleo-reconstructed record spanning the period 762 to 2005—were used in the Study to characterize historical streamflow patterns and variability. Period comparisons are made between the full extent of the data and a more recent period. For the observed dataset spanning 1906 to 2007, the second comparison period (1978 to 2007) was selected as the most recent (based on available natural flow records) 30-year period because it captures the recent drought period and the apparent climate shift after 1977 (IPCC, 2007). For the Paleo dataset spanning 762 to 2005, the second comparison period selected was 1906 to 2005 so that direct comparisons could be made of the observed and paleo timeframes. Annual flows and moving averages for 3, 5, 10, 20, and 30 years were computed for the two time periods so that differences in mean flows and variability of flows could be accessed. Annual flows and moving averages were also used to evaluate minimum and maximum streamflows. Exceedance probability plots were used to evaluate the likelihood of annual flows to exceed a specified streamflow value.

One future streamflow projection data set was represented in the Downscaled GCM Projected scenario. In this scenario, the routed streamflow from the VIC simulations driven by 112 climate projections for the period 1950 to 2099 were used to characterize natural flows at each of the 29 flow locations. VIC-simulated runoff from each grid cell was routed to the outlet of each watershed (the 29 flow locations) using VIC's offline routing tool (Lohmann et al., 1996; 1998). The routing tool processed individual cell runoff and baseflow terms and routed the flow based on flow direction and flow accumulation inputs derived from digital elevation models. Flows were output in both daily and monthly time steps. Only the monthly flows were used in the analysis for the Study. VIC routed flows are considered "natural flows" in that they do not include effects of diversions, imports, storage, or other human management of the water resource. Bias-correction was applied to the VIC-simulated flows to account for any systematic bias in the hydrology model or data sets.

Annual streamflows for both the historical analysis and future water supply scenarios were analyzed to provide an estimate of the inter-annual variability, or deficit and surplus conditions. Definitions of "drought" are often subjective in water planning. In general, droughts are defined as periods of prolonged dryness. The inter-annual variability of the climate and hydrology of the Southwest imply basins may be in frequent states of drought. As part of the analysis conducted for this report, different averaging periods for determining and measuring deficits (cumulative volume below some reference) were considered. The definition used in the Technical Report is the following: a deficit occurs whenever the 2-year average flow falls below the long-term mean annual flow of 1906 to 2007. The use of a 1-year averaging period was discarded because it implied that any 1 year above the 15-million-acre-feet Lees Ferry natural flow would break a multi-year deficit. The use of a 2-year averaging period implies that it may take 2 consecutive above-normal years (or 1 extreme wet year) to end a drought. For a basin with sizable reservoir storage in comparison to its mean flow such as the Colorado River, it may take several years to alleviate storage deficits. Averaging periods of 1 to 10 years were evaluated, following research by Timilsena et al. (2009). The 2-year averaging period appeared to produce similar deficits as the longer-averaging periods, and was thus selected as a useful indicator.

A summary of the streamflow data sources used in each of the water supply scenarios is included below.

4.1 Observed Natural Streamflows used in the Observed Resampled Scenario

The natural streamflows were obtained for the 1906 to 2007 period at the 29 flow locations commonly used by the Reclamation for planning. Reclamation uses data collected from the U.S. Geological Survey (USGS) and other gage sites, consumptive use records, records of reservoir releases, and other data to compute monthly natural flows at 29 locations throughout the Basin: 20 locations upstream of and including the Lees Ferry gaging station in Arizona, and 9 locations below the Lees Ferry gaging station (Prairie and Callejo, 2005).

Natural flow for the Upper Basin is computed as follows:

Natural Flow = Historic Flow + Consumptive Uses and Losses+/- Reservoir Regulation

Historical streamflow data were obtained from USGS Web pages. Total depletions in the form of consumptive uses and losses include the following: irrigated agriculture, reservoir evaporation, stockponds, livestock, thermal power, minerals, municipal and industrial, and exports/imports. Reservoir regulation includes mainstem reservoirs and non-mainstem reservoirs.

Natural flows for the Lower Basin comprise computed gains and losses (on the mainstem) and historical flows (on the tributaries). Computed gains and losses consider the following consumptive uses and losses: decree accounting reports (http://www.usbr.gov/lc/region/g4000/wtracct.html), evaporation (from Lakes Mead, Mohave, and Havasu), and phreatophytes. Reservoir regulation includes change in reservoir storage and change in bank storage. Historical flows on the tributaries (Paria, Virgin, Little Colorado, and Bill Williams Rivers) have not had the historical depletions added back to the gaged flow due to the state of current methods and processes. Thus, most Lower Basin flows should not be considered natural. For more detail on the treatment of the Lower Basin tributaries see *Technical Report C – Water Demand Assessment, Appendix C5 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System*.

Monthly intervening and total natural flow for the 29 locations are available. “Intervening” flows represent the flow generated between two locations, but do not include the cumulative contribution of the locations upstream. “Total” flows, on the other hand, include the local intervening flow and all upstream flows from that location.

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

4.2 Paleo Reconstructed Streamflow used in the Paleo Resampled Scenario

The natural streamflows in the Paleo Resampled scenario were derived from streamflow reconstructions at Lees Ferry from tree-ring chronologies for the period of 762 to 2005. The reconstructed streamflows at Lees Ferry were derived from ecologically contrasting tree-ring sites in the southern Colorado Plateau during the past 2 millennia (Meko et al., 2007). Streamflow values were disaggregated, spatially, and temporally, to the 29 locations by Reclamation (Prairie and Rajagopalan, 2007; Prairie et al., 2008).

4.3 Paleo Conditioned Streamflow used in the Paleo Conditioned Scenario

The Paleo Conditioned scenario blends the observed historical record and Paleo-reconstructed record to generate future inflow scenarios that comprise magnitudes of the historical record and state information from the Paleo record provided by Reclamation (Prairie and Rajagopalan, 2007; Prairie et al., 2008).

4.4 Future Streamflow Projections used in the Downscaled GCM Projected Scenario

The Downscaled GCM Projected scenario includes VIC hydrologic model traces of future streamflows for the 1950 to 2099 period from 112 GCM realizations for the 29 streamflow locations within the Basin. VIC model results were provided by Reclamation from work conducted for the West-Wide Climate Risk Assessment study (Reclamation, 2011).

5.0 References

Becker, E.J., E.H. Berbery, and R.W. Higgins. 2011. "Modulation of Cold-Season U.S. Daily Precipitation by the Madden–Julian Oscillation." *J. Climate*, 24, 5157–5166.

Bond, N. A., and G.A. Vecchi. 2003. "The influence of the Madden–Julian oscillation on precipitation in Oregon and Washington." *Wea. Forecasting*, 18, 600–613.

Bureau of Reclamation (Reclamation). 2010. Colorado River Natural Flow and Salt Data. Retrieved December 2010, from http://www.usbr.gov/lc/region/g4000/NaturalFlow/supportNF.html.

Bureau of Reclamation (Reclamation). 2011. *SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011*.

Cayan, D.R., K.T. Redmond, and L.G. Riddle.1999. "ENSO and Hydrologic Extremes in the Western United States." *Journal of Climate*, 12: 2881-2893.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith. 2006. "The Community Climate System Model Version 3 (CCSM3)." *J Climate*, 19(11):2122-2143.

Daly, C., G.H. Taylor, W. P. Gibson, T.W. Parzybok, G. L. Johnson, and P. Pasteris. 2000. "High-quality spatial climate data sets for the United States and beyond." *Transactions of the American Society of Agricultural Engineers*, 43**:** 1957-1962.

Diaz, H.F., and G.N. Kiladis. 1992. "Atmospheric Teleconnections Associated with the Extreme Phases of the Southern Oscillation." Diaz, H.F., and V.A. Markgraf (eds.), *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation.*

Diansky, N.A., and E.M. Volodin. 2002. "Simulation of present-day climate with a coupled atmosphere-ocean general circulation model." *Izv Atmos Ocean Phys* (English translation) 38(6):732-747.

Delworth, T.L., et al. 2006. GFDL's CM2 global coupled climate models part 1: formulation and simulation characteristics. *J Climate* 19:643-674.

Furevik, T., M. Bentsen, H. Drange, I.K.T. Kindem, N.G. Kvamstø, and A. Sorteberg. 2003. "Description and evaluation of the bergen climate model: ARPEGE coupled with MICOM." *Clim Dyn* 21:27-51.

Flato, G.M., and G.J. Boer. 2001. "Warming Asymmetry in Climate Change Simulations." *Geophys. Res. Lett.*, 28:195-198.

Gordon C., C. Cooper, C.A. Senior, H.T. Banks, J.M. Gregory, T.C. Johns, , J.F. B. Mitchell, and R.A. Wood. 2000. 'The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments." *Clim Dyn* 16:147-168.

Hidalgo, H. G. 2004. "Climate precursors of multi-decadal drought variability in the western United States" *Water Resour. Res.*, 40, W12504, DOI:10.1029/2004WR003350.

Hu, Q., and S. Feng. 2010. "Influence of the Arctic oscillation on central United States summer rainfall." *J. Geophys. Res.*, 115, D01102. DOI: 10.1029/2009JD011805.

Institut Pierre Simon Laplace. 2005. "The new IPSL climate system model: IPSL-CM4." *Institut Pierre Simon Laplace des Sciences de l'Environnement Global*.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Emissions Scenarios. Special Report of the Intergovernmental Panel on Climate Change* [Nakicenovic, N., and R. Swart, (eds.)].

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Quin, M. Manning,, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, (eds.)].

Joint Institute for the Study of the Atmosphere and Ocean. 2010. Retrieved Marh 30, 2011 from http://jisao.washington.edu/pdo/.

Jungclaus, J.H., M. Botzet, H. Haak, N. Keenlyside, J-J Luo, M. Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner. 2006. "Ocean circulation and tropical variability in the AOGCM ECHAM5/MPI-OM." *J Climate* 19:3952-3972.

K-1 Model Developers. 2004. "K-1 coupled model (MIROC) description, K-1 technical report, 1." In: *Frontier Research Center for Global Change*. Hasumi, H., Emori, S. (eds). Center for Climate System Research

Legutke, S., and R. Voss. 1999. *The Hamburg Atmosphere-Ocean Coupled Circulation Model ECHO-G. Technical report, No. 18*.

Lohmann, D., R. Nolte-Holube, and E. Raschke. 1996. "A large-scale horizontal routing model to be coupled to land surface parameterization schemes." *Tellus*, 48: 708-721.

Lohmann, D., E. Raschke, B. Nijssen, and D.P. Lettenmaier. 1998. "Regional Scale Hydrology: I. Formulation of the VIC-2L Model Coupled to a Routing Model." *Hydrological Sciences Journal*, 43, 131-141.

Mantua, N.J., and S.R. Hare, S.R. 2002. "The Pacific Decadal Oscillation." *Journal of Ocean*, 58: 35-42.

Maurer, E.P. 2007. "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios." *Climatic Change*, Vol. 82, No. 3-4, 309-325, DOI: 10.1007/s10584-006-9180-9.

Maurer, E. P., L. Brekke, T. Pruitt, and P.B. Duffy. 2007. "Fine-Resolution Climate Projections Enhance Regional Climate Change Impact Studies." *Eos, Transactions, American Geophysical Union*, 88 (47), 504.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15(22), 3237-3251.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughs, and M.W. Salzer. 2007. "Medieval Drought in the Upper Colorado River Basin." *Geophysical Research Letters*, 34(5), L10705, DOI: 10.1029/2007GL029988.

Mo, K.C., J.E. Schemm, and S. Yoo. 2009. "Influence of ENSO and the Atlantic Multi-Decadal Oscillation on Drought over the United States." *Journal of Climate*, 22(22), 5962-5982. DOI:10.1175/2009JCLI2966.1.

Mote, P., M. Clark, and A. Hamlet. 2008. “Variability and Trends in Mountain Snowpack in Western North America. 20th Conference on Climate Variability and Change”. American Meteorological Society. New Orleans, Louisiana.

Mote P.W., and E.P. Salathé. 2010. “Future climate in the Pacific Northwest.” *Climatic Change*, 102, 29–50. DOI 10.1007/s10584-010-9848-z.

Molotch, N. P., S.R. Fassnacht, M.T. Colee, T. Bardsley, and R.C. Bales. 2001. “A comparison of spatial statistical techniques for the development of a validation dataset for mesoscale modeling of snow water equivalence.” *Eos Trans*. AGU, 82(47), Fall Meet. Suppl., F553.

National Oceanic and Atmospheric Administration (NOAA). 2010. Retrieved June 30, 2011, from http://www.ncdc.noaa.gov/oa/climate/normals/usnormalsprods.html.

National Oceanic and Atmospheric Administration (NOAA). 2011. Retrieved June 30, 2011, from http://www.ncdc.noaa.gov/oa/climate/normals/usnormals.html.

National Resources Conservation Service. 2011. Retrieved June 30, 2011 from http://www.wcc.nrcs.usda.gov/snow/.

Prairie, J., and R. Callejo. 2005. *Natural Flow and Salt Computation Methods, Calendar Years 1971-1995*. U.S. Department of the Interior, Bureau of Reclamation, Salt Lake City, Utah, Boulder City, Nevada.

Prairie, J., and B. Rajagopalan. 2007. "Stochastic Streamflow Generation Incorporating Paleo-Reconstruction." Proceedings of the World Environmental and Water Resources Congress, Tampa, Florida.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp. 2008. “A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleoreconstructed Data.” *Water Resources Research.* Vol. 44, W06423, DOI: 10.1029/2007WR006684.

Russell, G.L., J.R. Miller, D. Rind, R.A. Ruedy, G.A. Schmidt, and S. Sheth. 2000. “Comparison of model and observed regional temperature changes during the past 40 years.” *J Geophys Res* 105:14891-14898.

Redmond, K.T., and R.W. Koch. 1991. “Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices.” *Water Resources Research*, 27, 2381–2399.

Salathé, E.P. 2005. “Downscaling simulations of future global climate with application to hydrologic modeling.” *Int J Climatol*, 25, 419–436.

Salas-Mélia, D., F. Chauvin, M. Déqué, H. Douville, J.F. Gueremy, P. Mareut, , S. Planton, J.F. Royer, and S. Tyteca. 2005. “Description and validation of the CNRM-CM3 global coupled model, CNRM working note 103.”

Timilsena J., T. Piechota, G. Tootle, and A. Singh. 2009. “Associations of interdecadal/interannual climate variability and long-term Colorado River Basin streamflow.” *J. Hydrol*. 365(3-4), 289-301, DOI:10.1016/j.jhydrol.2008.11.

U.S. Department of the Interior. 2004. “Climatic Fluctuations, Drought, and Flow in the Colorado River Basin, U.S. Geological Survey.” *USGS Fact Sheet 2004-3062*, version 2.

University of East Anglia Climatic Research Unit. 2010. Retrieved March 30, 2011 from http://www.cru.uea.ac.uk/cru/data/soi/.

Washington W.M., J.W. Weatherly, G.A. Meehl, A.J. Semtner, T.W. Bettge, A.P. Craig, W.G. Strand, J. Arblaster, V.B. Wayland, R. James, Y. Zhang. 2000. "Parallel climate model (PCM) control and transient simulations." *Clim Dyn* 16:755-774.

Webb, R.H., and J.L. Betancourt. 1992. "Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona: U.S. Geological Survey." *Water-Supply Paper 2379*.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier. 2002. "Long-range experimental hydrologic forecasting for the Eastern United States." *J. Geophysical Research-Atmospheres*, 107(D20), 4429, DOI:10.1029/ 2001JD000659.

Wood, A.W., L.R. Leung, V. Sridhar, and D.P. Lettenmaier. 2004. "Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs." *Climatic Change*, 15, 189–216.

Yukimoto S., A. Noda, A. Kitoh, M. Sugi, Y. Kitamura, M. Hosaka, K. Shibata, S. Maeda, and T. Uchiyama. 2001. "The new Meteorological Research Institute coupled GCM (MRI-CGCM2) – model climate and variability." *Pap Meteorol Geophys* 51:47-88.

Appendix B3
Supplemental Analysis of Future Climate Data

Appendix B3 — Supplemental Analysis of Future Climate Data

During the development of the hydrologic simulations under historical and projected climate forcings as part of the Water Supply Assessment, biases were observed for the overlapping period of 1950 to 1999 as compared to the natural flow data set. These biases are due to differences between the General Circulation Model (GCM)-simulated historical climate and observed climate data, differences in hydrology model inputs and parameterization, and differences between the Variable Infiltration Capacity (VIC)-simulated hydrologic responses and observed watershed responses implied in the natural flows. This appendix describes analysis that was conducted to determine the effect of bias in climate forcings used to simulate streamflows and whether choice of the daily weather generation (temporal disaggregation) method significantly affects this bias.

Although it was expected that biases would exist due to the hydrology model and historical gridded climate, it was believed that these biases would be similar (same magnitude and direction) when comparing to simulations of GCM-simulated historical climate. However, the biases were found to be substantially different when comparing three representations of the historical period (1950 to 1999) streamflow: 1) natural flows derived from gage measurements; 2) VIC-simulated flows when forced with observed (derived) historical climate; and 3) VIC-simulated flows when forced with GCM-simulated historical climate. For example, the VIC simulation using observed historical climate for 1950 to 1999 suggested an over-estimation of flows in the Colorado River at Lees Ferry, Arizona. However, the same VIC model, when forced with GCM-simulated historical climate, produced an under-estimation of flow. Without a robust streamflow bias correction method, it is possible that the effects of climate change could be overstated.

Several potential causes of streamflow bias were investigated to support the use of the downscaled climate projections on a daily scale and to support the development of a streamflow bias correction method. The biases were investigated through various separate analyses using the historical climate forcings and VIC model simulations for the period of 1950 to 1999. The following areas related to climate forcing bias were investigated:

1. ***Bias due to 2-degree climate forcings***. The projected climate forcings are bias corrected through the bias correction and spatial downscaling (BCSD) process at a common 2-degree scale. The forcings are corrected for each month, but residual bias at seasonal, annual, and multi-year scales are possible.
2. ***Bias due to 1/8th-degree spatial downscaling***. Because the BCSD process corrects for month-specific bias at the 2-degree scale, it is possible that residual bias exists after performing spatial downscaling to the 1/8th-degree scale.
3. ***Bias due to daily weather generation method***. Two data sets were available using slightly different methods to temporally disaggregate monthly climate data into daily weather inputs. It is possible that the choice of method could affect the resulting streamflow bias.

The evaluation of each of the potential causes of bias is discussed further in the following sections. In each of these evaluations, GCM-simulated historical climate was compared to historical observed climate from Maurer et al. (2002) for the period of 1950 to 1999. Although any of the 112 downscaled climate projections could have been used, one particular projection (Trace 44 – sresa2.ccma_cgcm3_1.4) was selected for presentation of results. Biases were found to be relatively consistent across the range of projections.

Analyses were performed for precipitation at representative grid cells at the locations in the Colorado River Basin (Basin) shown in table B3-1. However, results are shown for the grid cell at the Colorado River at the Glenwood Springs, Colorado, location.

TABLE B3-1
Locations where Evaluation of Biases Was Performed (decimal latitude and longitude)

No.	Location	Nearest Grid Cell (Latitude, Longitude)
1	Colorado River at Lees Ferry, Arizona	36.4375, -112.0625
2	Green River at Green River, Utah	38.8125, -111.3125
3	San Juan River near Bluff, Utah	35.5625, -110.6875
4	Colorado River near Cisco, Utah	38.6875, -109.6875
5	Colorado River above Imperial Dam, Arizona	32.9375, -114.8125
6	Colorado River at Glenwood Springs, Colorado	39.3125, -107.5625
7	Colorado River below Fontenelle Reservoir, Wyoming	42.0625, -110.8125
8	San Juan River near Archuleta, New Mexico	36.6875, -107.8125
9	Colorado River below Davis Dam, Arizona-Nevada	35.1875, -115.0625
10	Taylor River below Taylor Park Reservoir, Colorado	38.8125, -106.5625

1.0 Bias Due to 2-degree Climate Forcings

The BCSD method adjusts monthly biases in climate projections at the 2-degree spatial scale. By construction, the method preserves monthly precipitation and temperature statistics to the observed for the overlapping 1950 to 1999 period at the 2-degree spatial scale. However, because hydrologic responses are dependent on seasonal, annual, and sometimes multi-year sequences of precipitation and temperature, the bias was evaluated for longer temporal scales.

Figures B3-1A and B3-1B show the observed, raw GCM, and the bias corrected GCM monthly precipitation for grid cell at the Colorado River at Glenwood Springs location. As can be seen from the figures, the raw GCM results need to be bias corrected to achieve similar statistics to the observed in the overlapping period. The raw GCM biases appear to be largest in the December and January months. However, after bias correction, the monthly statistics are preserved for all months as compared to the observed (bias corrected [BC] line is same as observed line in figures).

FIGURE B3-1A
Comparison of Monthly Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data, January–June
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

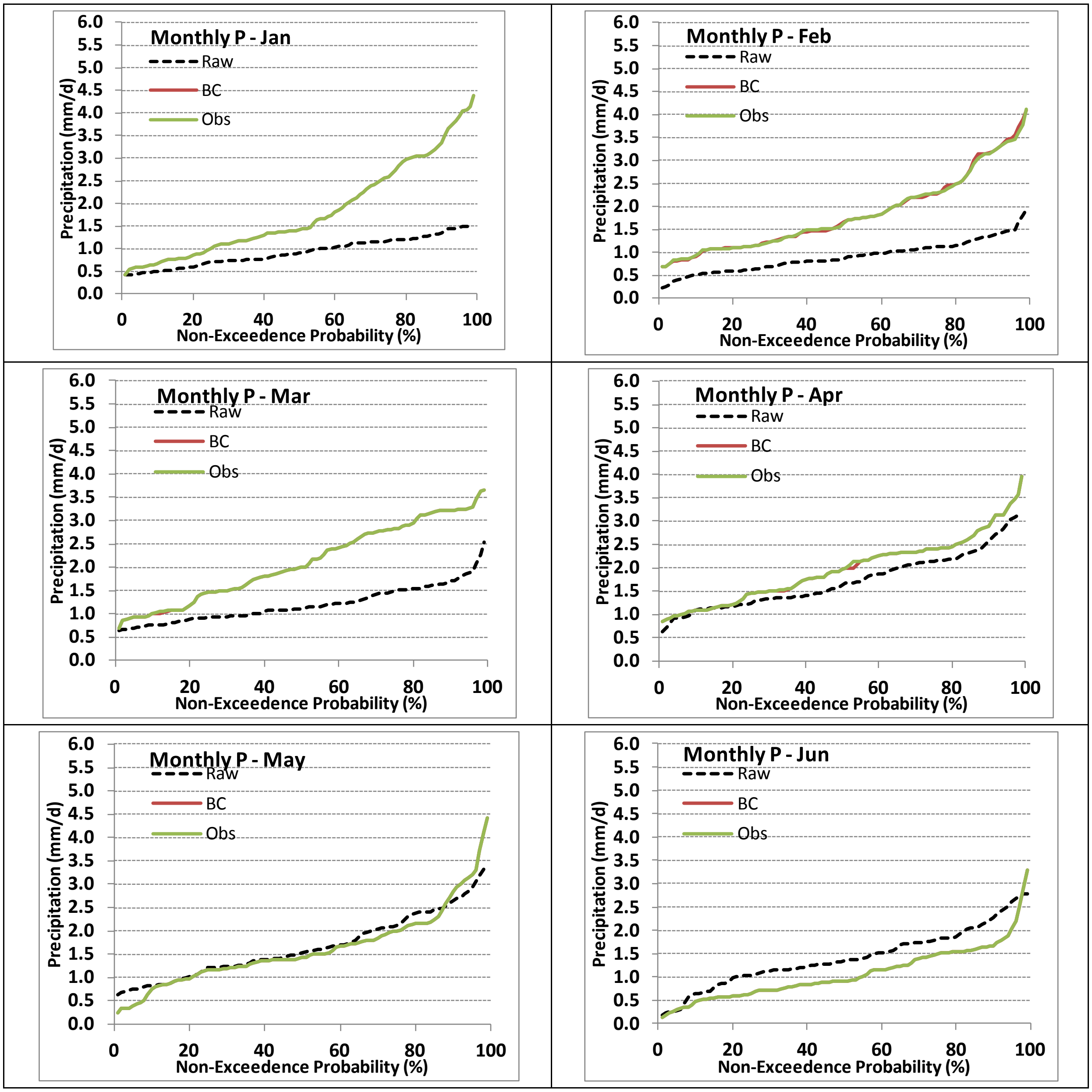


FIGURE B3-1B
Comparison of Monthly Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data, July–December
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

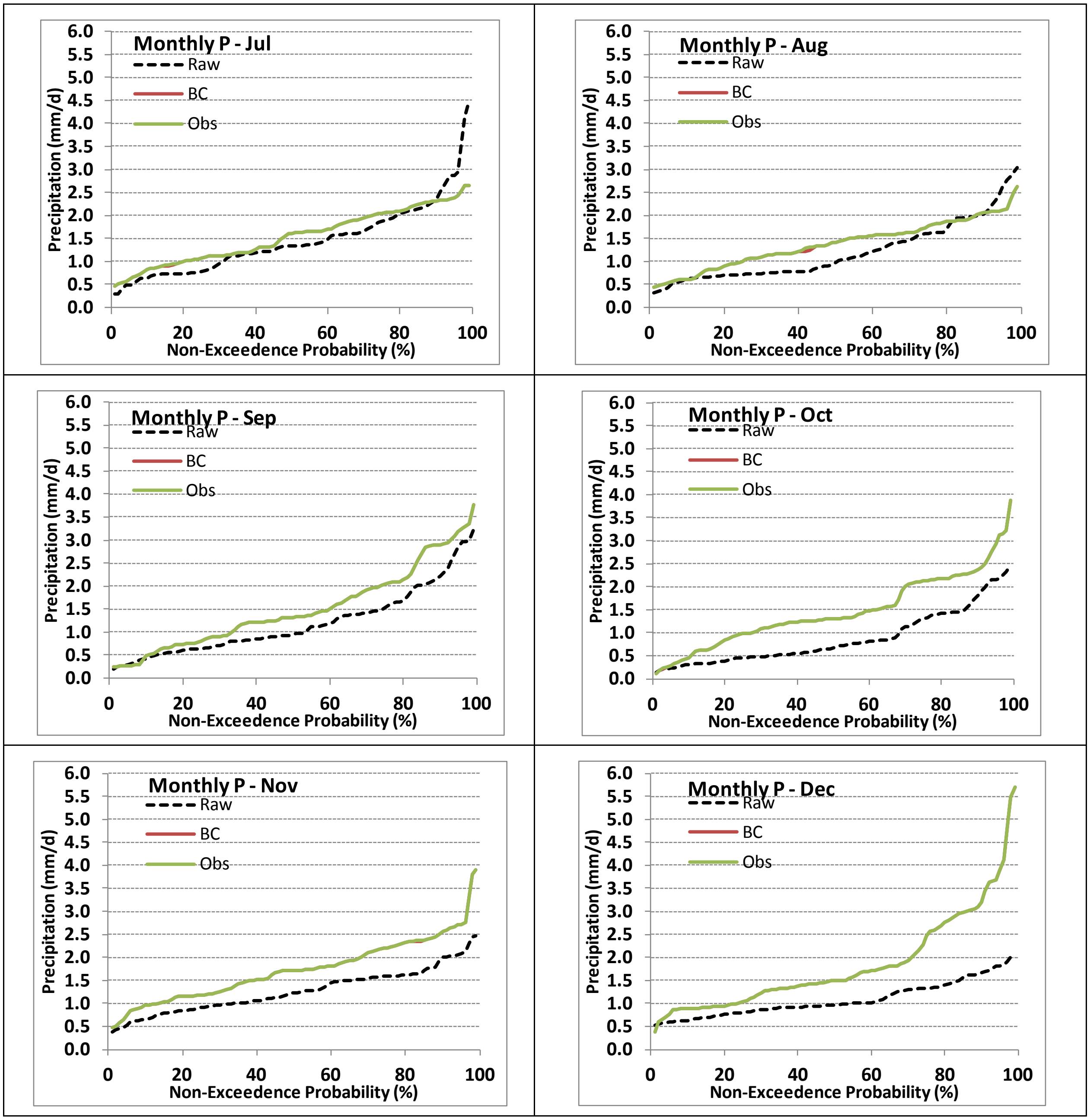


Figure B3-2 shows the same information for the seasonal and annual time scales. As shown in this figure, despite monthly BC, residual bias exists at seasonal and annual scales as compared to the observed. The 2-degree bias corrected GCM precipitation appears to underestimate the periods of high seasonal precipitation. The underestimation of high seasonal precipitation appears to be caused by differences in sequences of wet months within the season between the GCM-simulated historical climate and the observed climate. The seasonal bias is largest during the winter (January, February, and March) and fall (October, November, and December) and relatively small in other seasons. However, small bias continues to persist at annual scales as shown in the bottom panel of the figure. Figure B3-3 also indicates that GCM-simulated historical climate (after bias correction) retains bias at multi-year scales. In almost all multi-year averaging periods, the observed precipitation is larger than the bias corrected GCM precipitation, although the magnitude of this impact has not been isolated.

The temperature biases (not shown) are significantly less than precipitation biases at all time scales and are not believed to represent a significant source of bias to streamflow assessments.

2.0 Bias Due to 1/8th-degree Spatial Downscaling

The BCSD method adjusts for monthly biases in climate projections at 2-degree spatial scale. By construction, the method preserves monthly precipitation and temperature statistics to the observed for the overlapping 1950 to 1999 period at the 2-degree spatial scale. However, to be useful for most watershed assessments, the climate information is needed at finer spatial scales. The spatial downscaling transforms the climate information to the 1/8th-degree scale. The 1/8th-degree spatial scale climate data were used as inputs into the VIC hydrologic model. Analyses were performed to investigate bias after downscaling to this finer spatial scale.

As shown in figures B3-4A and B3-4B, although there is generally agreement between the observed and simulated historical climate statistics at the 1/8th-degree scale, bias exists even at the monthly scale. As with the 2-degree climate information, the biases are largest in winter; particularly December and January. Biases continue to exist at the seasonal, annual, and multi-year scales (figure B3-5 and B3-6). These longer time-scale biases are larger at the 1/8th-degree than at the 2-degree spatial scales.

FIGURE B3-2
Comparison of Seasonal and Annual Precipitation Non-exceedance Probability Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GCM-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

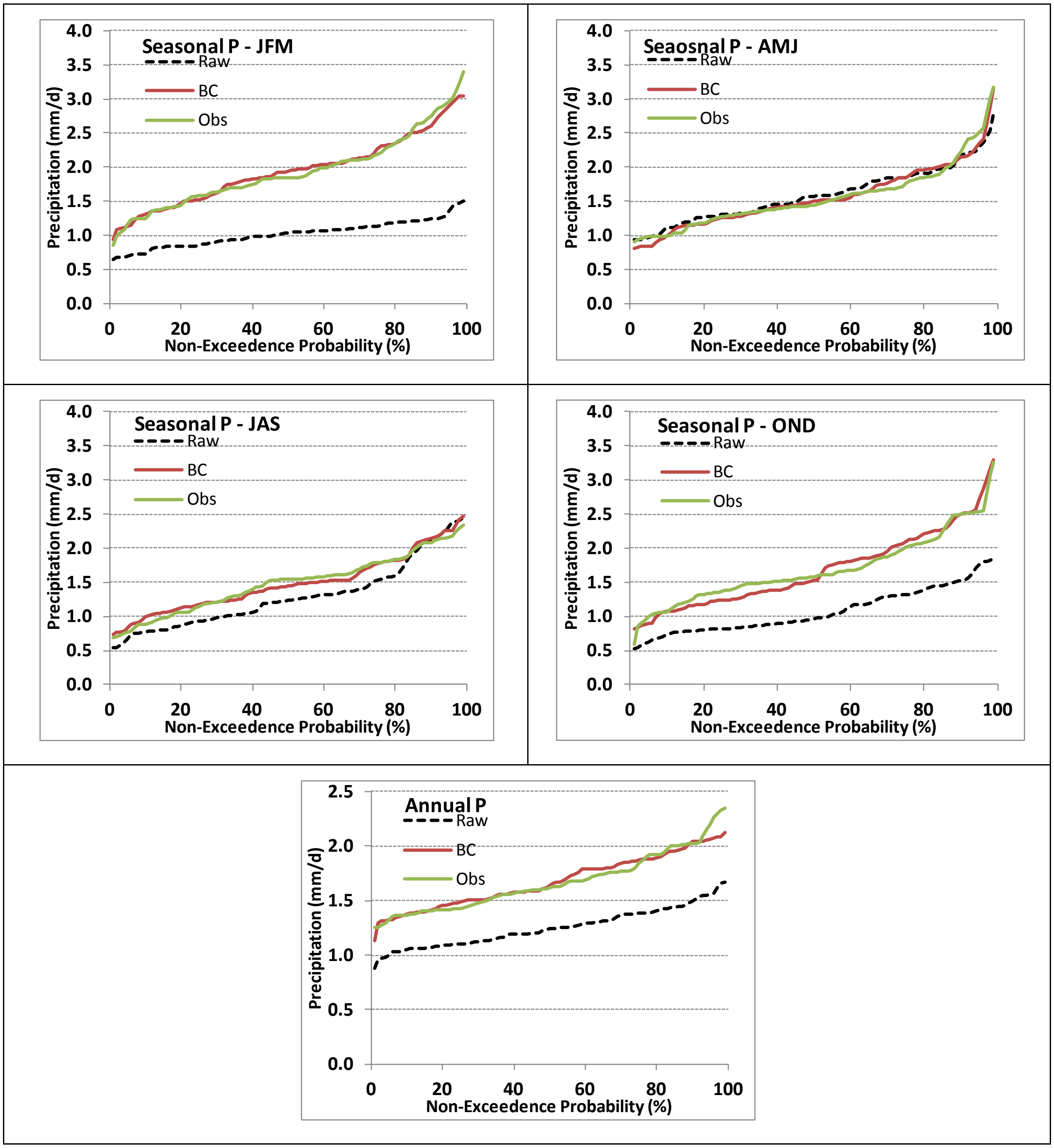


FIGURE B3-3
Comparison of Non-exceedance Probability for Precipitation Averaged over 2-year, 3-year, 5-year, and 10-year Periods, Using 2-degree Raw GCM (Raw), Bias Corrected GCM (BC), and Observation (Obs) Data
2-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from 2-degree spatially aggregated precipitation from Maurer et al. (2002).

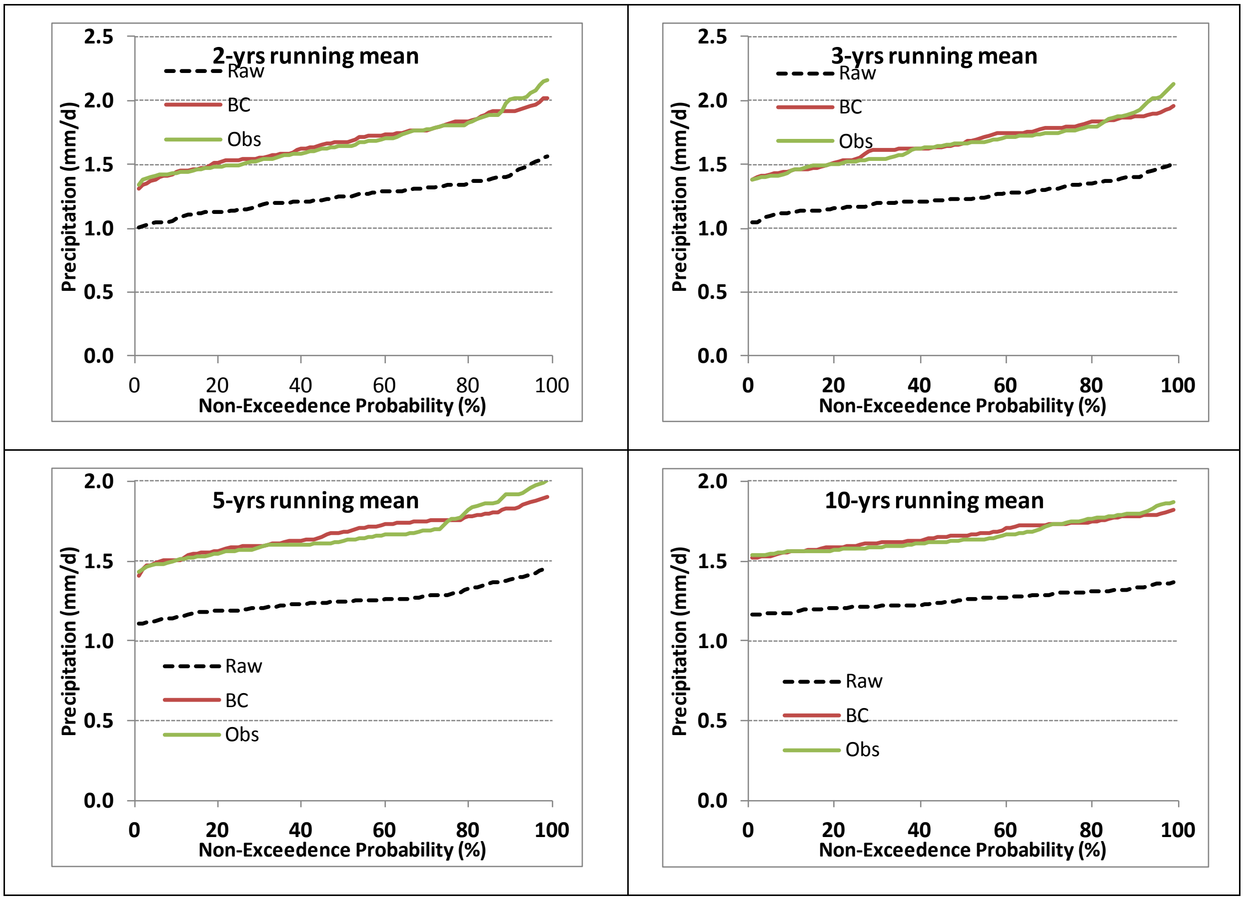


FIGURE B3-4A
Comparison of Monthly Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, January–June
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

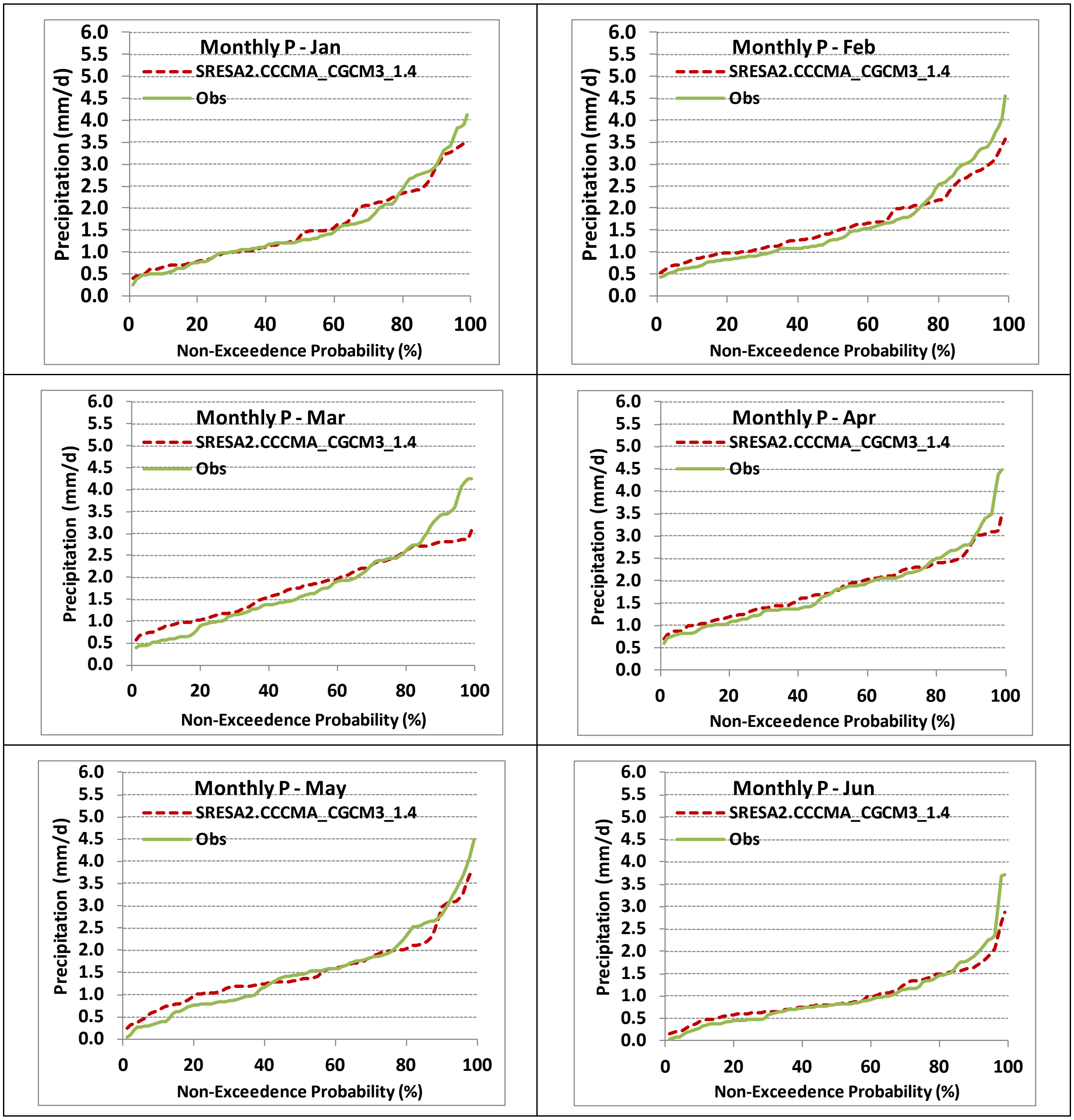


FIGURE B3-4B
Comparison of Monthly Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, July–December
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

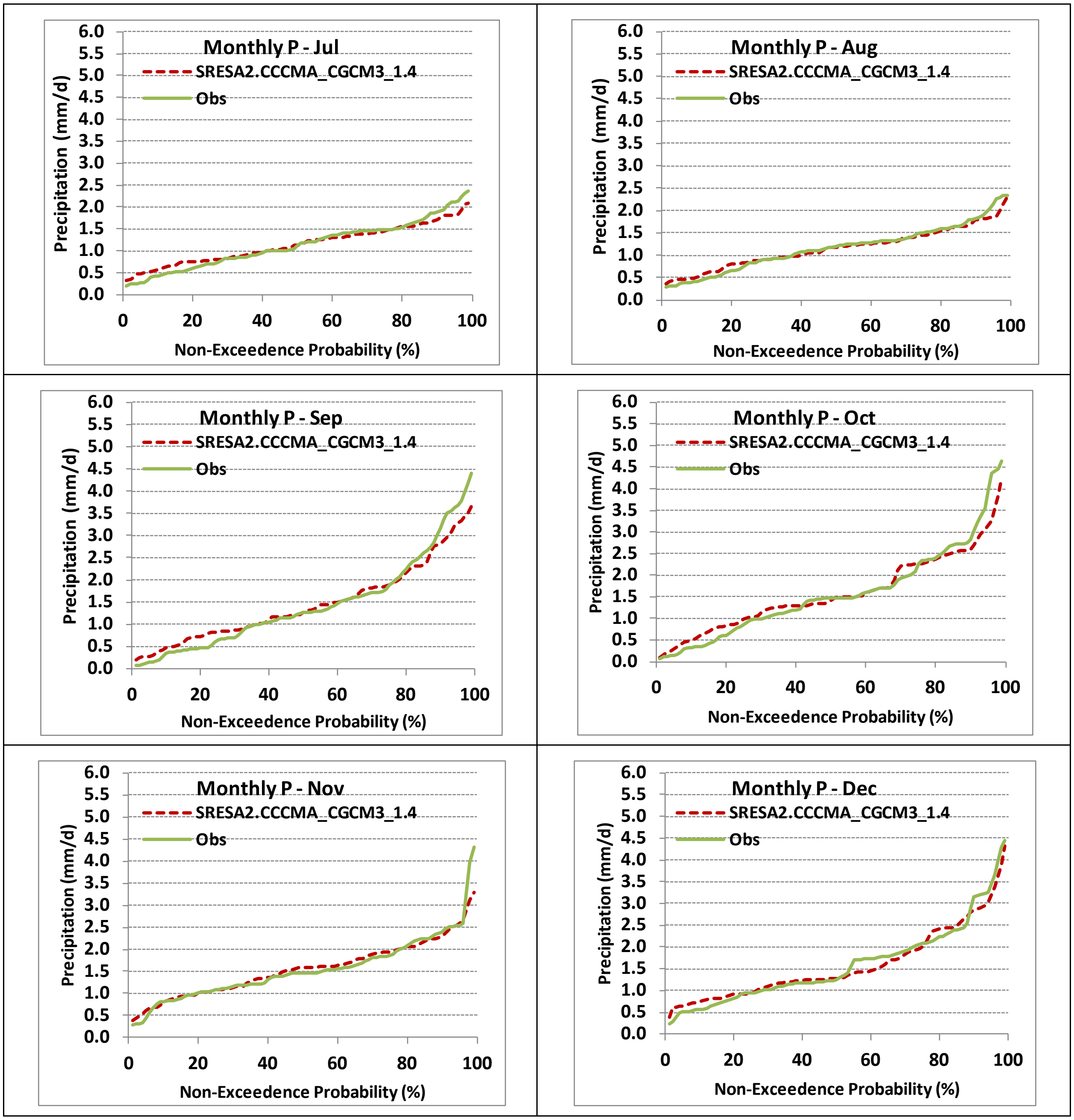


FIGURE B3-5
Comparison of Seasonal Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

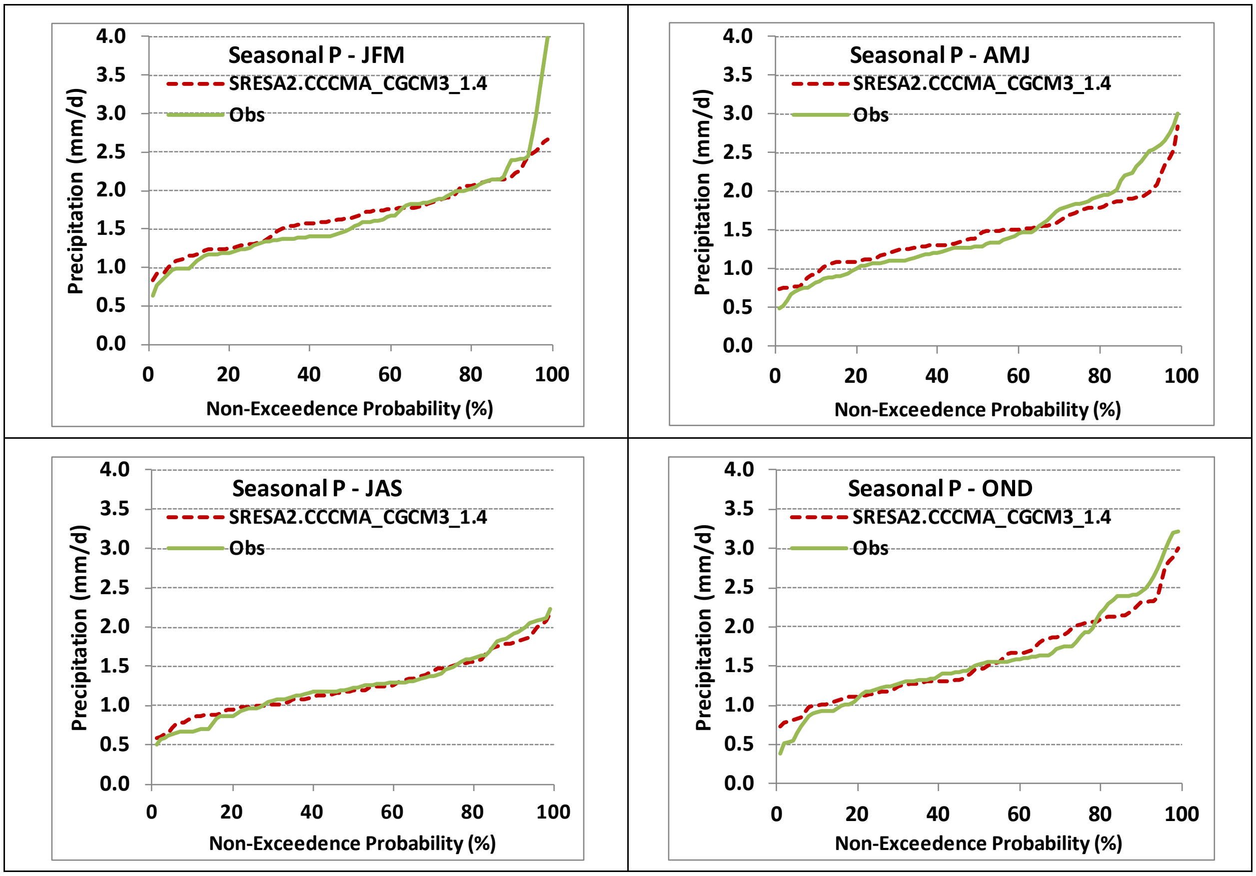


FIGURE B3-6
Comparison of Seasonal and Averaged over 2-year, 3-year, 5-year, and 10-year Periods, Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

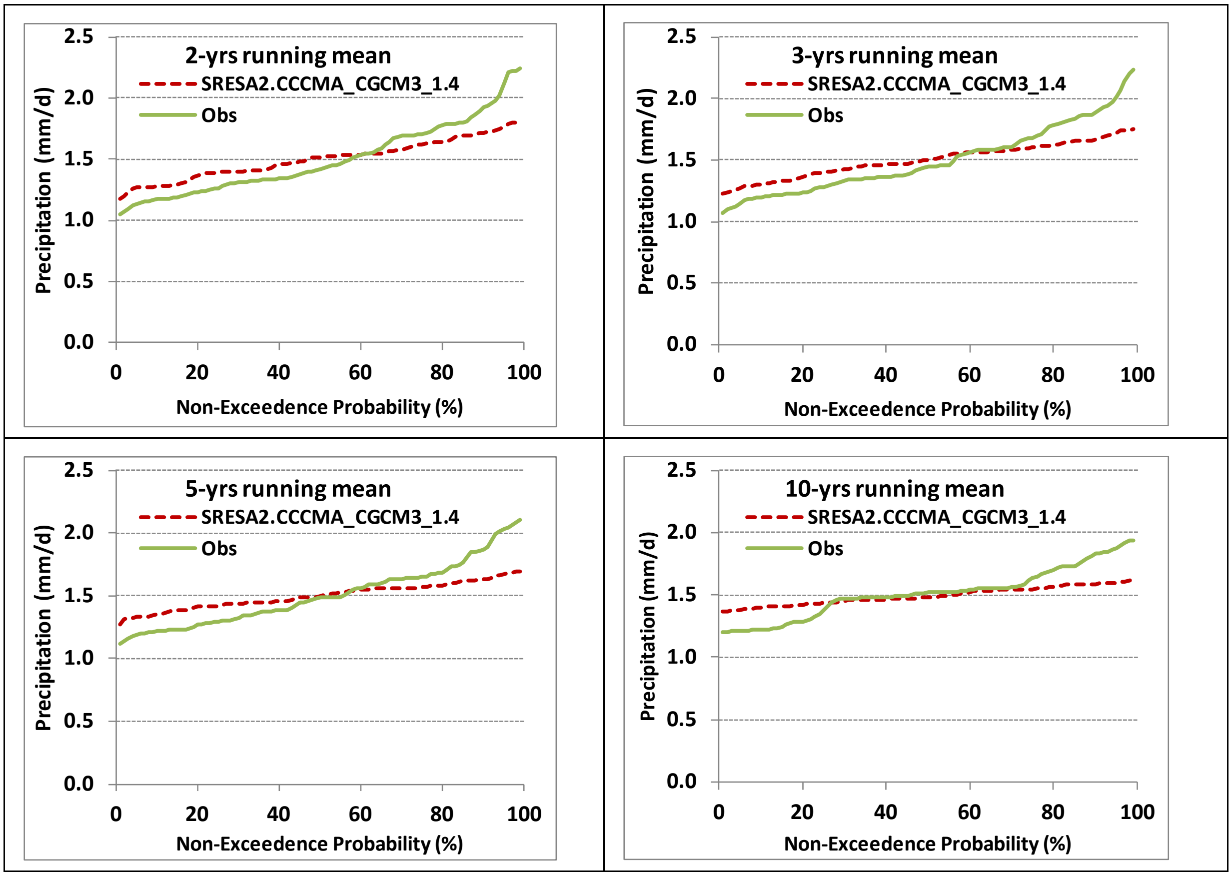
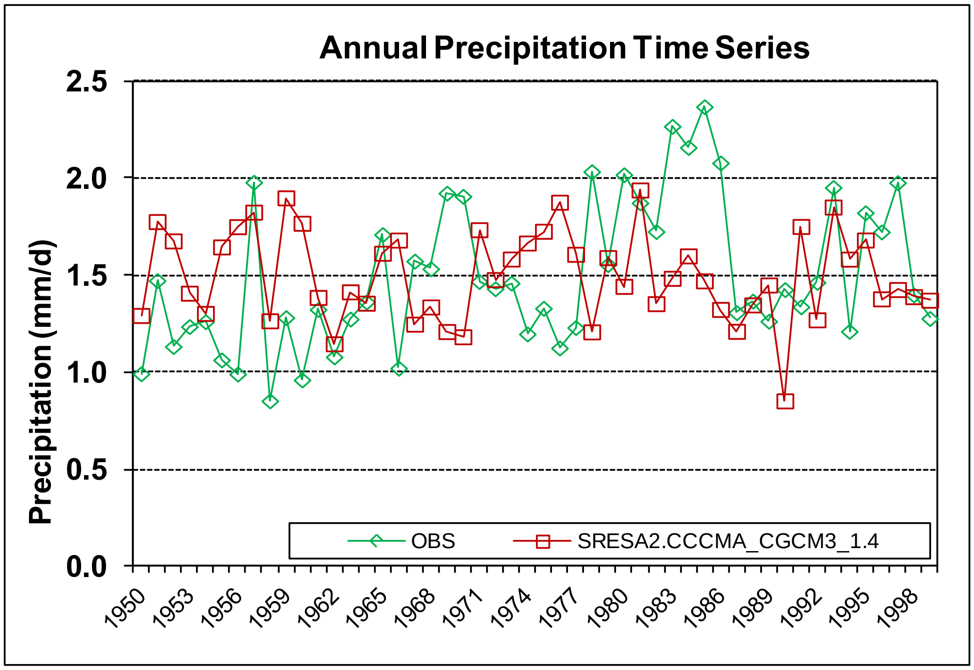


Figure B3-7 shows the annual time history of the observed precipitation and the simulated historical period precipitation for one particular GCM projection for 1950 to 1999. The GCMs are not expected to reproduce the identical sequences of observed precipitation due to differences between actual and simulated initial ocean and climate states, differences between actual and simulated emissions and other radiative forcings, and other model limitations. As shown in the figure, multi-year wet periods such as that observed in 1983 to 1986 are not expected to occur at the same time in the historical simulations, but are expected to be reproduced over some historical period. However, the magnitude of this wet persistence was not reproduced in the simulated climate (see figure B3-7). This under-representation of wet persistence appears to be common across all 112 projections.

FIGURE B3-7
Comparison of Annual Precipitation Non-exceedance Probability Using 1/8th-degree BCSD (sresa2.cccma_cgcm3_1.4) and Observed (Obs) Data, July–December
1/8th-degree grid cell near Colorado River at Glenwood Springs, Colorado location. GMC-simulated from Trace 44 – sresa2.cccma_cgcm3_1.4; Observation data from Maurer et al. (2002).

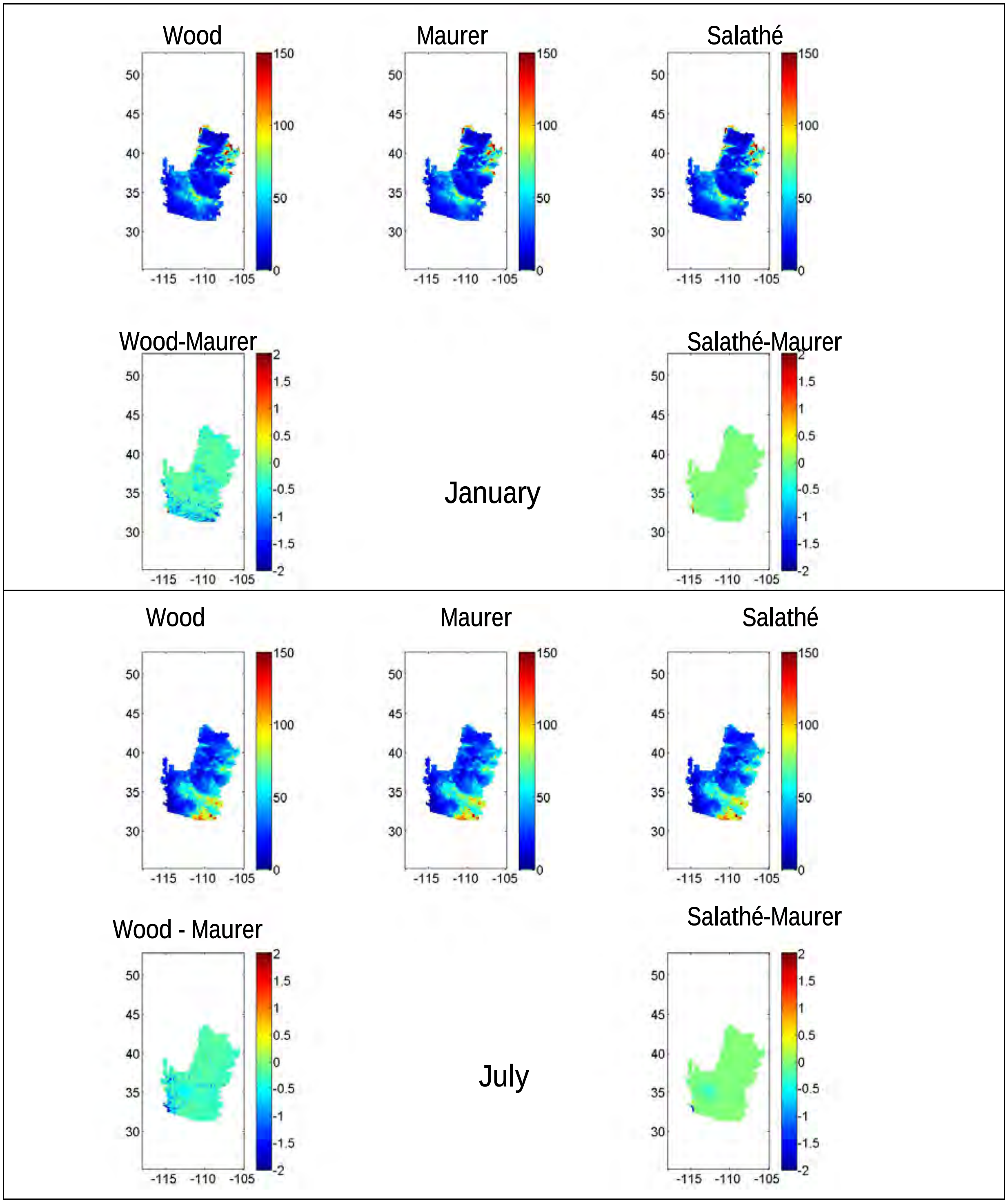


3.0 Comparison of Daily Weather Generation (Temporal Disaggregation) Methods

As part of the assessment of future climate data and their impact on streamflow, two different daily weather datasets were available for the Colorado River Basin Water Supply and Demand Study (Study). The two methods used to develop these datasets are: 1) a method developed by the Climate Impacts Group at the University of Washington (Salathé, 2005) and that used in the Bureau of Reclamation's (Reclamation) West-Wide Climate Risk Assessment (WWCRA) (Reclamation, 2011), and 2) the method developed by Wood et al. (2002) and used in previous Colorado River VIC assessments (Christensen and Lettenmaier, 2007). Both daily weather generation methods preserve monthly total precipitation from the downscaled climate projections and use the historical database to develop realistic daily storm patterns through a temporal disaggregation method. The differences between the two approaches are relatively subtle, but it was found that VIC hydrologic model results were sensitive to the choice of method.

Analysis of the precipitation statistics between the two methods indicates no significant differences at the *monthly* scale. The observational data set was derived from Maurer et al. (2002). Comparisons have been prepared for one downscaled climate projection: Trace 44 – sresa2.cccma_cgcm3_1.4 under the two different daily weather generation methods. Figure B3-8 illustrates a graphical comparison of the monthly precipitation for January and July between the two methods and the observed. The differences between simulated and observed are generally zero, as can be seen from the bottom plots. However, some small differences occur in the extreme southwest of the Basin under the Wood methodology.

FIGURE B3-8
Comparison of Monthly Precipitation between Observational Data (Maurer et al., 2002) and Downscaled Precipitation (Wood et al. 2002; Salathe, 2005), January and July
Only January and July monthly averaged values in millimeters per day [mm/d] are shown. Downscaled climate data for Wood et al. (2002) and Salathé (2005) are from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.



To better understand the differences in storm patterns generated under each weather generation method, analyses of precipitation events greater than certain thresholds were conducted. Figure B3-9 shows the comparison for 2 mm/d (0.08 inches per day [in/d]) and 20 mm/d (0.8 in/d) precipitation events. Figure B3-10 shows the comparison for 50 mm/d (2 in/d) and 100 mm/d (4 in/d) precipitation events. In general, the method (Salathé, 2005) applied in the WWCRA produces precipitation events more similar to those in the observed record, although differences exist at all precipitation thresholds.

FIGURE B3-9
Comparison of Number of Days (percent) with Precipitation Greater than 2 mm/d (top) and 20 mm/d (bottom) between Maurer et al. (2002) Observed Precipitation and GCM Downscaled Precipitation Using Two Methods (Wood et al., 2002; Salathé, 2005)
GCM downscaled precipitation from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.

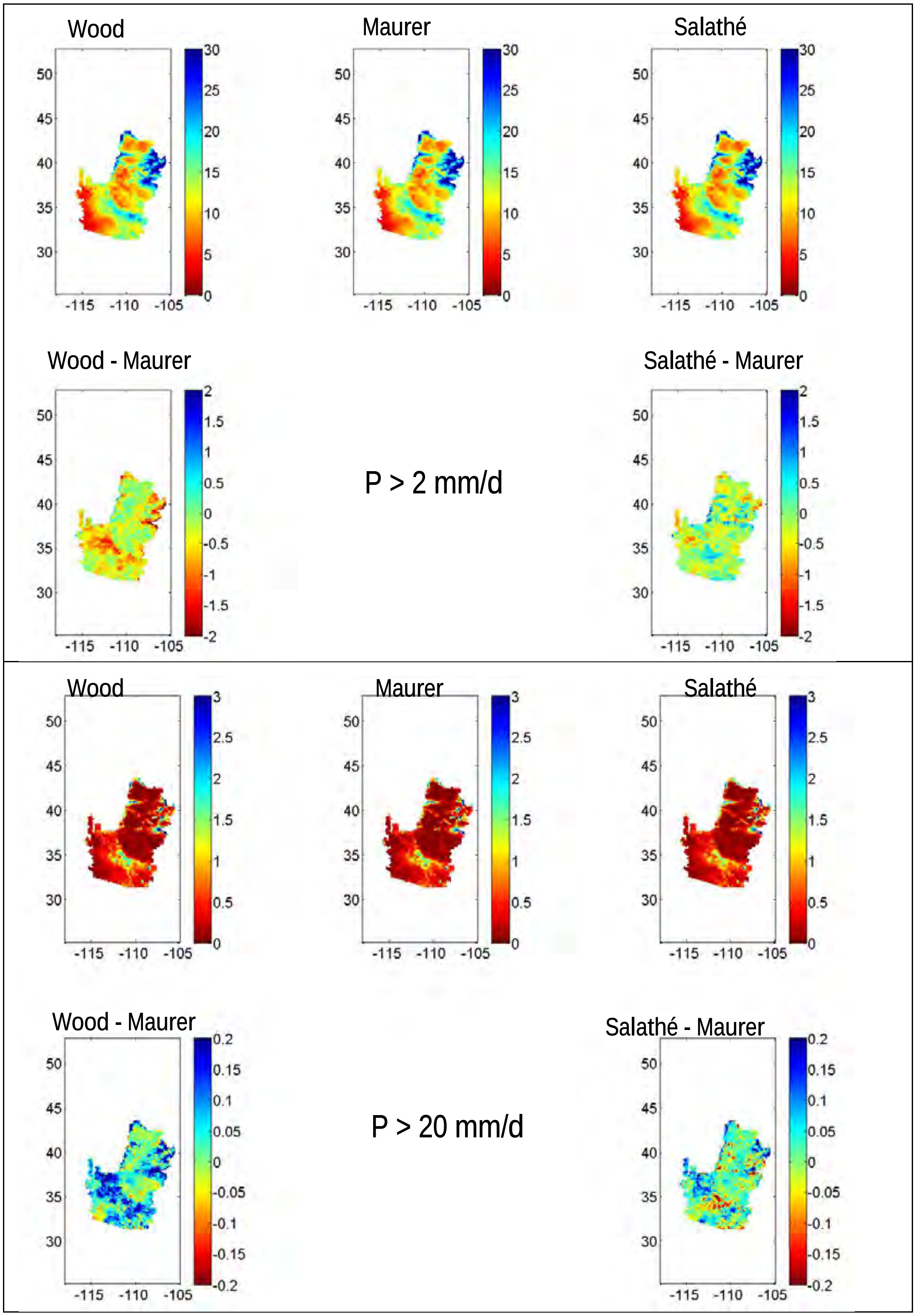
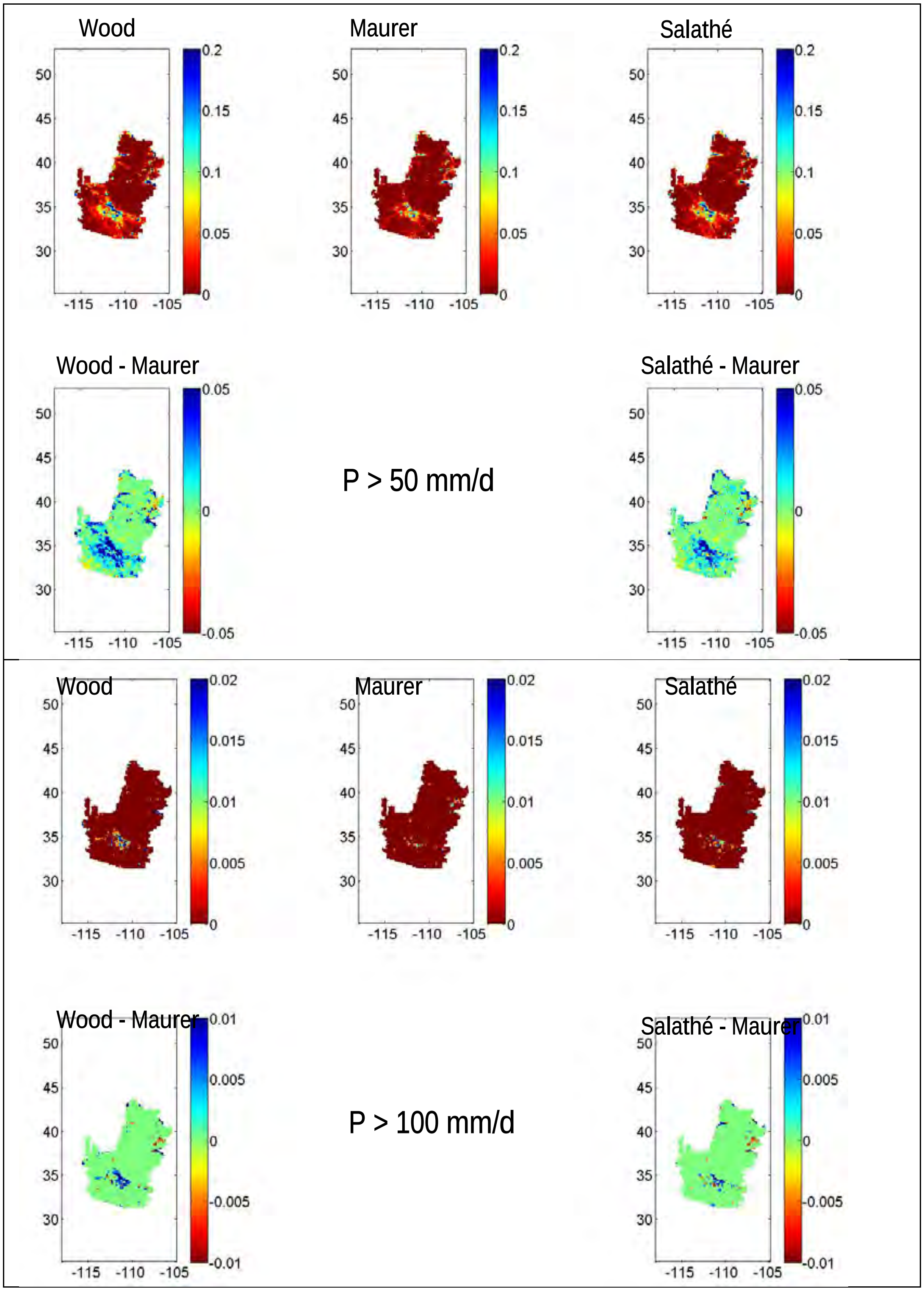
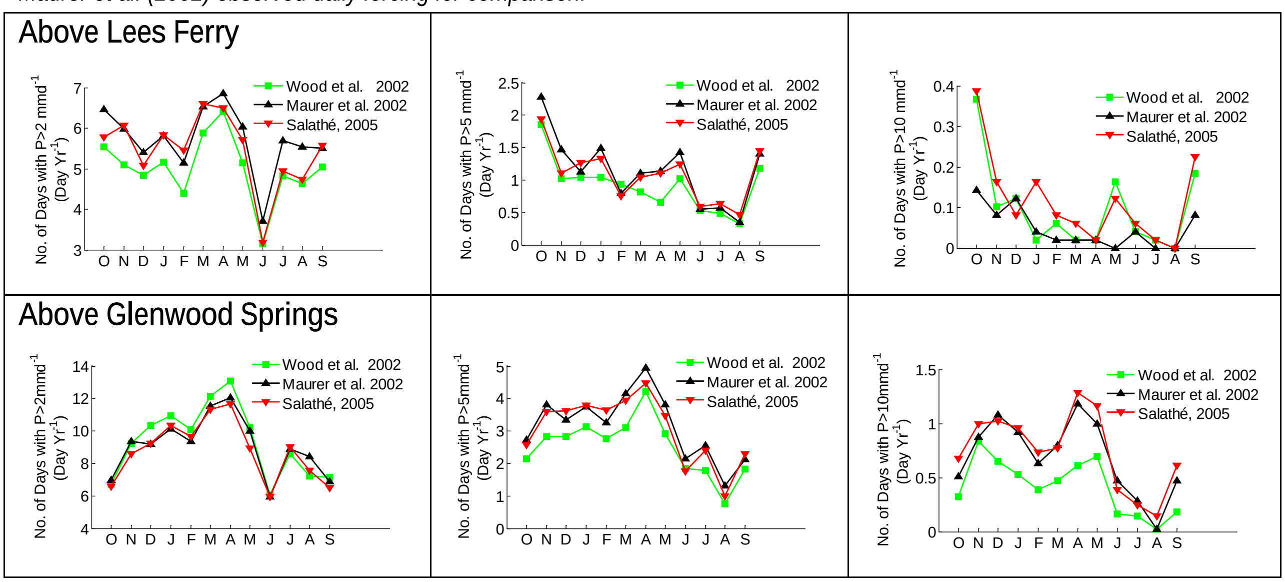


FIGURE B3-10
Comparison of Number of Days (percent) with Precipitation Greater than 50 mm/d (top) and 100 mm/d (bottom) between Maurer et al. (2002) Observed Precipitation and GCM Downscaled Precipitation Using Two Methods (Wood et al., 2002; Salathé, 2005)
GCM downscaled precipitation from Trace 44 – sresa2.cccma_cgcm3_1.4. Maps are shown with decimal latitude and longitude coordinates.



The analysis shown in the spatial figures was performed for each grid cell independently and did not reflect spatial correlation during storm events. In figure B3-11, the spatially averaged precipitation for all grid cells above Lees Ferry was analyzed for thresholds likely to produce runoff (2 mm/d, 5 mm/d, and 10 mm/d). The method employed by Salathé (2005) and incorporated in the WWCRA appeared to more faithfully reflect observed precipitation frequencies for this spatial area. This method produced significantly more representative precipitation frequencies to the observed than that used in the previous VIC simulations, particularly at the 2–mm/d and 5–mm/d thresholds. At the 10–mm/d threshold, both methods overestimated the frequency of occurrence; however, the observed frequency was already low. For the area above Glenwood Springs (figure B3-11), the method applied by Salathé was significantly better at all precipitation frequencies considered.

FIGURE B3-11
Number of Days per Year (averaged over the 1950–1999 period) with Precipitation Larger than Selected Thresholds (2 mm/d, 5 mm/d, and 10 mm/d)
Computed from the daily precipitation over the period 1950–1999 using spatially averaged precipitation for all grid cells above Colorado River at Lees Ferry contributing area (top) and above Colorado River at Glenwood Springs (bottom). Wood et al.(2002) and Salathé (2005) are from downscaled data from Trace 44 – sresa2.cccma_cgcm3_1.4. Values are also shown from Maurer et al. (2002) observed daily forcing for comparison.



Finally, VIC simulations were prepared using the two methods of daily weather generation for the historical period 1950 to 1999 using identical GCM-simulated monthly climate. These simulations were compared to the VIC simulation using historical observed climate; and the natural flow estimates for the Colorado River at Lees Ferry, Arizona. The VIC historical validation (VIC simulation using the historical observed methodology) suggests an overestimation of mean annual flows by about 4 percent. Of the two daily weather generation methods, the VIC simulation using the Salathé method is closest to this historical validation simulation (table B3-2); 2.8 percent compared to 5.8 percent using the Wood et al. (2002) method. Although the differences between methods appear to be relatively small in percentage terms, the difference in mean annual flows is nearly 500,000 acre-feet between methods.

TABLE B3-2
Annual Average Streamflows at Colorado River at Lees Ferry Computed from the Period 1950–1999

Colorado River at Lees Ferry Estimate (1950–1999)	Mean Annual Flow (million acre-feet)	% Difference from Natural Flow Estimate (% Difference from Validation)
Reclamation Natural Flow Estimate	14.673	–
VIC Historical Validation	15.248	3.9%
VIC Historical Simulation (Trace 44; Wood et al., 2002)	14.362	-2.1% (-5.8%)
VIC Historical Simulation (Trace 44; Salathé, 2005)	14.839	1.1% (-2.8%)

4.0 Conclusions

Based on the analysis of climate data, biases, and weather generation methods, several conclusions can be drawn. First, although the bias correction of GCM-simulated climate occurs to preserve monthly statistics, biases for seasonal, annual, and multi-year exist even at the 2-degree spatial resolution. Second, spatial downscaling of climate data to the 1/8th-degree resolution, required for hydrologic analysis, introduces small biases at the monthly scale that do not exist in the 2-degree data. Finally, even under identical monthly climate forcings, the method for developing daily patterns of precipitation is important and can contribute to substantially different streamflow results. The analysis included in the Study addresses these findings by adopting the Salathé approach of daily weather generation because it produced smaller overall biases as compared to the historical validation simulations. In addition, the analysis indicates that biases in climate data and hydrologic simulation will continue to be present, and that a final adjustment to VIC-simulated streamflows is necessary to use these flows in comparable fashion in systems modeling. For these reasons, a method for bias correction of resulting VIC-simulated flows is incorporated and discussed in appendix B4.

5.0 References

Bureau of Reclamation (Reclamation). 2011. West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections. Technical Memorandum No. 86-68210-2011-01.

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." *Hydrology and Earth System Sciences*, 11, 1417–1434.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15(22), 3237–3251.

Salathé E.P. 2005. "Downscaling simulations of future global climate with application to hydrologic modeling." *Int J Climatol*, 25:419–436.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier. 2002. "Long-range experimental hydrologic forecasting for the Eastern United States." *J. Geophysical Research-Atmospheres*, 107(D20), 4429, DOI:10.1029/ 2001JD000659.

Appendix B4
Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations

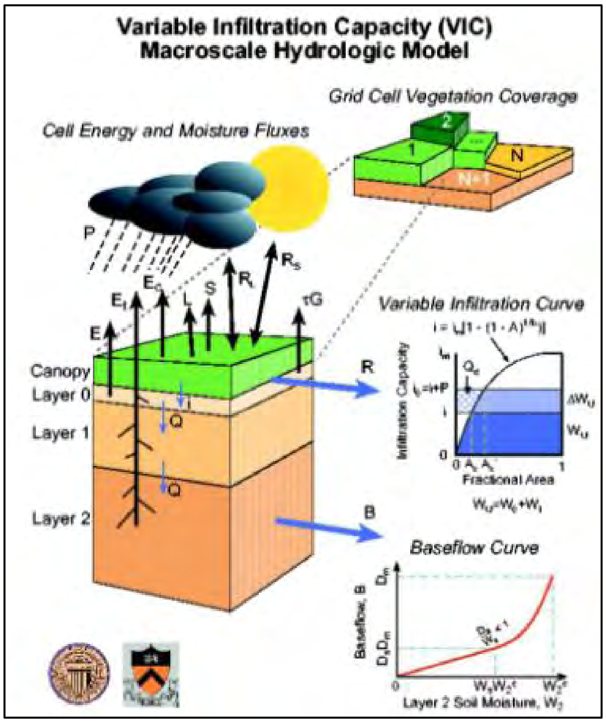
Appendix B4 — Variable Infiltration Capacity (VIC) Hydrologic Modeling Methods and Simulations

The Variable Infiltration Capacity (VIC) model (Liang et al., 1994; Liang et al., 1996) is the hydrology model used in the Colorado River Basin Water Supply and Demand Study (Study) to simulate the hydrologic response of the Colorado River Basin (Basin) to historical and future climate. The results from VIC simulations were used to describe the range of streamflows under the Downscaled General Circulation Model (GCM) Projected scenario. Each of the 112 downscaled climate projections was used as input into the VIC hydrology model. The VIC hydrology model uses the climate projections along with land cover, soils, elevation, and other watershed information to simulate hydrologic fluxes. The hydrologic fluxes were then routed to each of the 29 natural flow locations using a routing network derived from the topography. The result of this approach is 112 unique sequences of natural flow under future climate projections. However, the simulated natural flows can contain significant monthly and annual biases when compared to the natural flows of the historical period. These biases are generally small for mainstem Colorado River locations, but can be large for smaller watersheds and in areas where the VIC model was not specifically calibrated. To account and compensate for these biases, the VIC-simulated streamflows for both the historical and future periods were first adjusted for biases before incorporating into systems modeling. This appendix describes the VIC hydrology model, methods, and simulations included in the Study.

1.0 General Description of VIC

The VIC model (Liang et al., 1994; Liang et al., 1996) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. It incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. VIC is considered a macro-scale hydrologic model in that it is designed for larger basins with fairly coarse grids. In this manner, it accepts input meteorological data directly from global or national gridded databases or from GCM projections. To compensate for the coarseness of the discretization, VIC is unique in its incorporation of sub-grid variability to describe variations in the land parameters as well as precipitation distribution. Parameterization within VIC is performed primarily through adjustments to parameters describing the rates of infiltration and baseflow as a function of soil properties, as well as the soil layers' depths. When simulating in water balance mode, VIC is driven by daily inputs of precipitation, maximum and minimum temperature, and wind speed. The model internally calculates additional meteorological forcings such as short- and long-wave radiation, relative humidity, vapor pressure, and vapor pressure deficits. Rainfall, snow, infiltration, evapotranspiration (ET), runoff, soil moisture, and baseflow are computed over each grid cell on a daily basis for the entire period of simulation. An offline routing tool then processes the individual cell runoff and baseflow terms and routes the flow to develop streamflow at various locations in the watershed. Figure B4-1 shows the hydrologic processes included in the VIC model.

FIGURE B4-1
Hydrologic Processes Included in the VIC Model



Source: http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview/ModelOverview.shtml

The VIC model has been applied to many major basins in the United States, including large-scale applications to California's Central Valley (Maurer et al., 2002; Brekke et al., 2008; Cayan et al., 2010), Colorado River Basin (Christensen and Lettenmaier, 2007), Columbia River Basin (Hamlet et al., 2010), and for several basins in Texas (Maurer et al., 2002; CH2M HILL, 2008). The VIC model has a number of favorable attributes for the Study, but VIC's three most significant advantages are that it has a reliable, physically based model of ET, it has a physically based model of snow dynamics, and it has been used for two studies of climate change in the Basin for which calibrated parameters are available.

2.0 VIC Modeling Methods Specific to the Colorado River Basin

2.1 Model Inputs

The VIC model was driven by meteorological forcing data. Although the model has some flexibility in what variables are required, forcing files typically include daily values for precipitation, maximum temperature, minimum temperature, and wind speed. The VIC model required that the forcing files be in either American Standard Code for Information Interchange or binary format, with one file for each grid cell of the simulation domain. The model grid for the Basin consists of approximately 4,500 grid cells at a 1/8th-degree latitude by longitude spatial resolution.

Daily gridded observed meteorology data were obtained from Santa Clara University (Maurer et al., 2002) for the period 1950 to 1999. Projections of monthly future climate data were obtained from the Lawrence Livermore National Laboratory under the World Climate Research Program's Coupled Model Intercomparison Project Phase 3 and using the weather general (temporal disaggregation) methods described in appendix B3. Wind speed in the future projections was not adjusted in these analyses because downscaling of this parameter was not available, nor well translated from global climate models to local scales.

2.2 VIC Model Processes and Output

The VIC model was simulated in water balance mode. In this mode, a complete land surface water balance is computed for each grid cell on a daily basis for the entire model domain. Unique to the VIC model is its characterization of sub-grid variability. Sub-grid elevation bands enable more-detailed characterization of snow-related processes. Five elevation bands are included for each grid cell. In addition, VIC also includes a sub-daily (1-hour) computation to resolve transients in the snow model. The soil column is represented by three soil zones extending downward from the land surface to capture the vertical distribution of soil moisture. The VIC model represents multiple vegetation types using the National Atmospheric and Space Administration's Land Data Assimilation System databases as the primary input data set.

For the simulations performed for the Basin, the following water balance parameters were produced as output on a daily and monthly time step: precipitation, runoff, baseflow, ET, soil moisture, and snow water equivalent. The runoff simulated from each grid cell was routed to various river flow locations using VIC's offline routing tool. The routing tool processes individual cell runoff and baseflow terms and routes the flow based on flow direction and flow accumulation inputs derived from digital elevation models. For the simulations performed for the Basin, intervening streamflow was routed to 29 locations that align with the 29 natural flow locations in the Colorado River Simulation System (CRSS), the Bureau of Reclamation's (Reclamation) long-term planning model and the primary modeling tool used in the Study. Flows are output in both daily and monthly time steps. Only the monthly flows were used in subsequent analyses. It is important to note that VIC routed flows are considered "naturalized" in that they do not include effects of diversions, imports, storage, or other human management of the water resource.

3.0 Colorado River Basin VIC Model Validation

A VIC model of the Basin was previously developed by the University of Washington (Christensen and Lettenmaier, 2007), and was provided to Reclamation for the Study. The VIC model was not further calibrated or refined as part of the Study, but the model performance over the 1950 to 1999 validation period is described in this section.

The VIC historical validation run was simulated on a daily time step over the 1950 to 1999 period. Historical observed climate inputs are from Maurer et al. (2002). Streamflow was routed to each of the 29 natural flow locations used by Reclamation in Basin planning. Figure B4-2 shows the validation results for the Colorado River at Lees Ferry, Arizona location. The VIC simulation results in an overestimation of mean annual flows of about 3.9 percent when compared to the Reclamation natural flow estimate. The validation run captured the low and moderate annual flows, but has a slight overestimation of the high annual flows. Simulated flows in April and May flows are higher than Reclamation calculated historical natural flows, while July and August flows are slightly lower. Simulated flows for Colorado River at Cisco, Green River at Green River, Utah, and the San Juan River near Bluff, Utah, are shown in figures B4-3 through B4-5. The simulated flows show a slight overestimation for the Colorado River at Cisco and Green River at Green River stations when compared to the Reclamation natural flow estimates, while an underestimation is apparent for the San Juan River near Bluff station. Pearson's linear correlation coefficient, bias, and root mean square error (RMSE) are computed using the observed naturalized and VIC-simulated streamflows as driven by Maurer et al. (2002) over the 1950 to 1999 validation period for all 20 locations in the Upper Basin. These results are summarized in table B4-1. In general, the VIC model appears to have relatively small biases for the larger watersheds as compared to the Reclamation natural flow estimates, but can be larger for smaller watersheds and in areas where the VIC model was not specifically calibrated. The VIC model appears to have higher biases in the upper watersheds and lower biases farther downstream as more watershed contributes to the flow.

FIGURE B4-2
VIC Validation Summary for Colorado River at Lees Ferry, Arizona

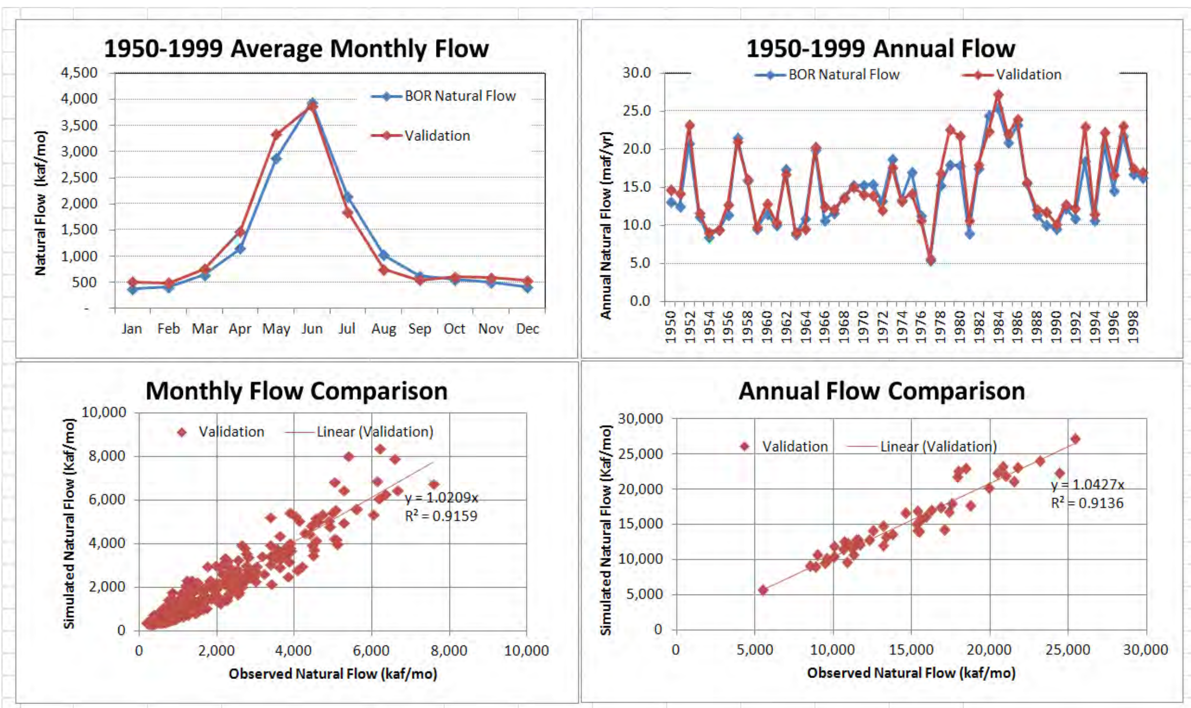


FIGURE B4-3
VIC Validation Summary for Colorado River at Cisco, Utah

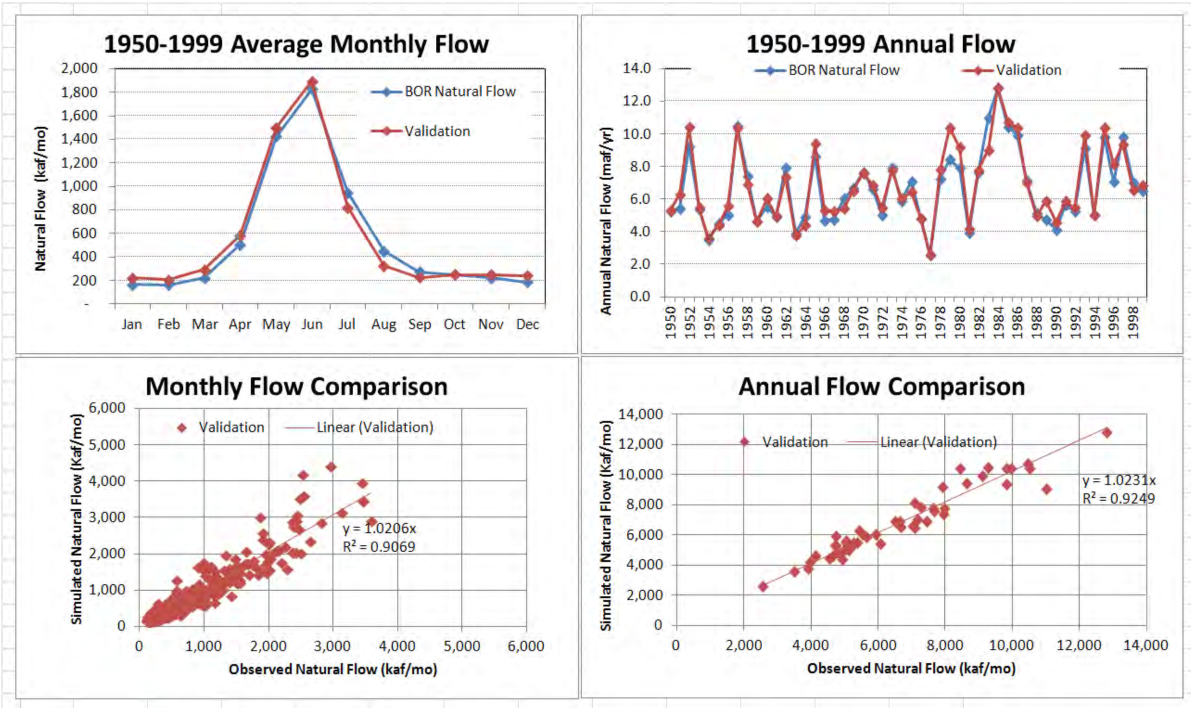


FIGURE B4-4
VIC Validation Summary for Green River at Green River, Utah

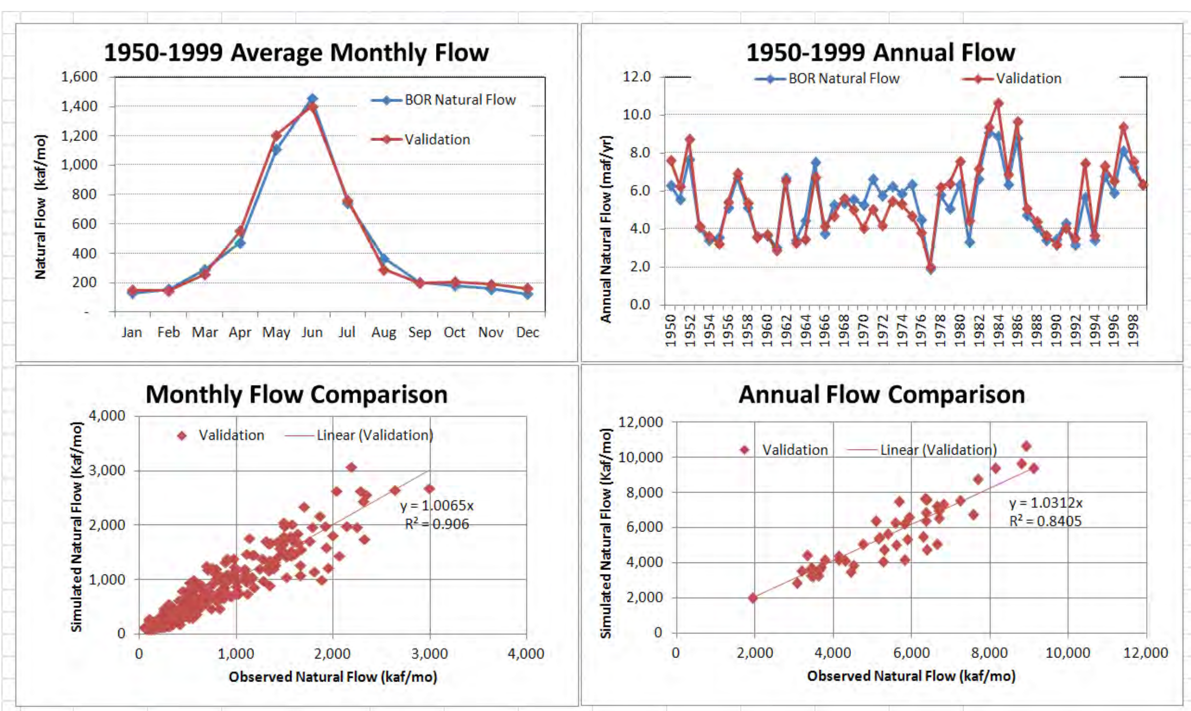


FIGURE B4-5
VIC Validation Summary for San Juan River near Bluff, Utah

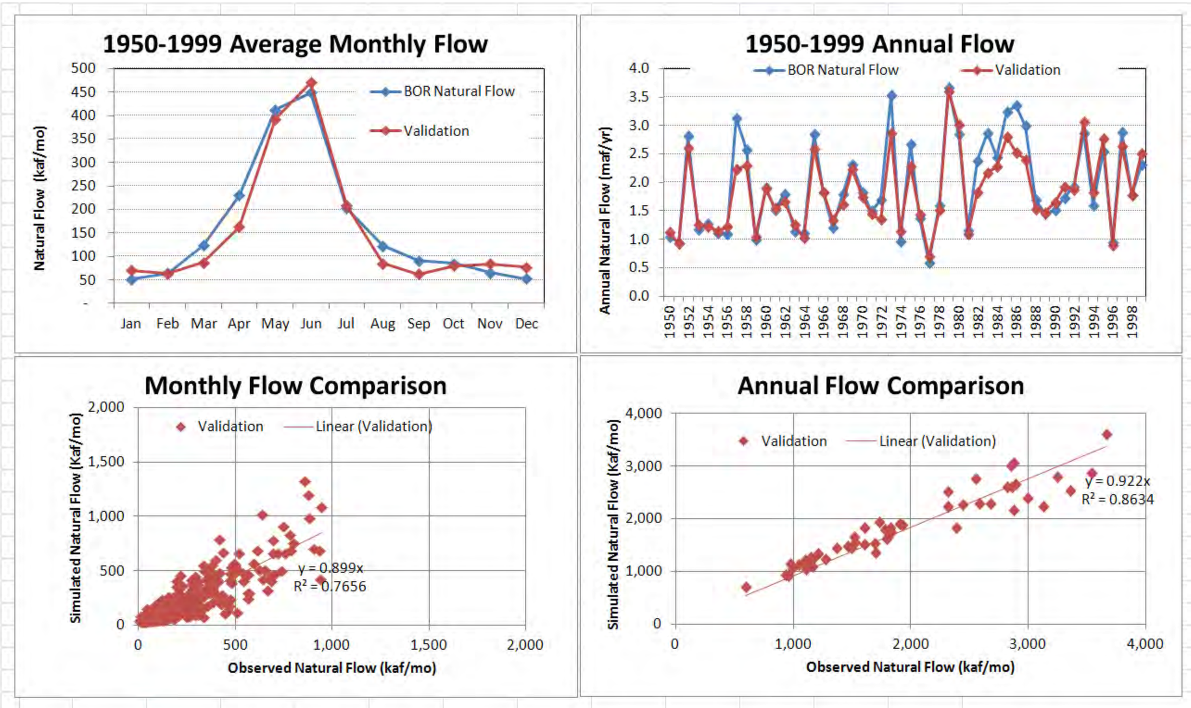


TABLE B4-1
Observed Annual Naturalized Streamflow and VIC-simulated Streamflow (with Maurer et. al [2002] historical meteorology) Comparison Statistics (1950–1999)

ID	Location	Obs. Nat. Flow (thousand acre-feet [kaf])	VIC Nat. Flow (kaf)	Bias (%)	Pearson's Linear Correl. Coef.	RMSE (kaf)	RMSE (% of mean flow)
1	Colorado River at Glenwood Springs, Colorado	2,071	2,192	5.8%	0.9	360.0	17.4%
2	Colorado River near Cameo, Colorado	3,489	3,741	7.2%	0.9	546.4	15.7%
3	Taylor River Below Taylor Park Reservoir, Colorado	148	172	15.9%	0.8	48.2	32.5%
4	Gunnison River at Blue Mesa Reservoir, Colorado	1,045	1,316	26.0%	0.9	332.3	31.8%
5	Gunnison River at Crystal Reservoir, Colorado	1,273	1,494	17.4%	0.9	325.5	25.6%
6	Gunnison River near Grand Junction, Colorado	2,304	2,336	1.4%	0.9	295.2	12.8%
7	Dolores River near Cisco, Utah	789	554	-29.7%	0.9	307.0	38.9%
8	Colorado River near Cisco, Utah	6,647	6,829	2.7%	1.0	640.4	9.6%
9	Green River below Fontenelle Reservoir, Wyoming	1,364	1,079	-20.9%	0.8	396.8	29.1%
10	Green R. near Green River, Wyoming	1,469	1,226	-16.5%	0.8	359.1	24.5%
11	Green River near Greendale, Utah	2,009	1,971	-1.9%	0.8	392.3	19.5%
12	Yampa River near Maybell, Colorado	1,210	1,086	-10.2%	0.9	196.4	16.2%
13	Little Snake River near Lily, Colorado	466	580	24.3%	0.8	173.1	37.1%
14	Duchesne River near Randlett, Utah	778	920	18.2%	0.9	291.1	37.4%
15	White River near Watson, Utah	557	525	-5.7%	0.8	167.1	30.0%
16	Green River at Green River, Utah	5,397	5,440	0.8%	0.9	785.7	14.6%
17	San Rafael River near Green River, Utah	161	273	69.1%	0.7	152.8	94.8%
18	San Juan River near Archuleta, New Mexico	1,028	869	-15.5%	0.9	268.2	26.1%
19	San Juan River Bluff, Utah	1,953	1,856	-5.0%	0.9	292.6	15.0%
20	Colorado River at Lees Ferry, Arizona	14,673	15,248	3.9%	1.0	1550.9	10.6%

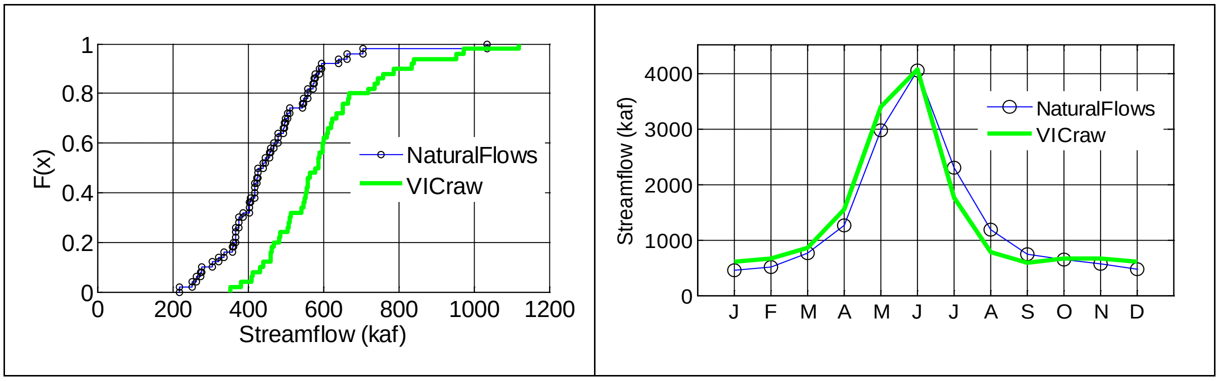
4.0 Application of Streamflow Bias Correction

The analysis presented in appendix B3 shows that there are some biases in the VIC streamflows as driven by GMC-simulated historic meteorological forcings in comparison with the naturalized streamflows for the Basin for the overlapping period 1950 to 1999. These biases result from several factors, including spatial and temporal errors in downscaled climate model forcings, complex groundwater interactions, and other complexities normally inherent to VIC hydrologic model parameter calibration. The analysis showed there are some uncertainties in the daily disaggregation method that was used to produce daily meteorological forcings from the monthly downscaled meteorology (see appendix B3). Daily meteorological data are required to drive the VIC. Moreover, there are uncertainties related to VIC model processes and parameter calibration demonstrated through comparisons of VIC-simulated historical streamflows with the naturalized streamflows for the Basin. Bias corrections of the downscaled climate model simulated VIC streamflows are performed to better reflect the statistics of the observed streamflows for the historical simulation period. This document describes the method developed to bias-correct the streamflows for the Basin. The method has been implemented for all 29 river locations for the period 1950 to 1999 for VIC simulation for each of the 112 projections. Results are presented for one particular projection (Trace 44 – sresa2.cccma_cgcm3_1.4) to demonstrate the process. VIC streamflows generated under future climate projections incorporate the same bias correction process before determining the flow projections for use in systems modeling.

The streamflow bias correction accounts for monthly and annual statistical bias at each of the 29 flow locations. Following the station-specific adjustments, the total Basin mass balance is again checked and adjustments are made such that flow continuity is maintained throughout the Basin. The streamflow bias correction involves the following steps:

1. Evaluate the monthly and annual bias in VIC-simulated streamflows as compared to the observed natural flows for each of the 29 locations. See Figure B4-6.

FIGURE B4-6
Comparisons of the January Cumulative Distribution Function (CDF) (left) and Mean Monthly (right) Streamflow Developed from VIC-simulated and Natural Streamflow
Colorado River at Parker Dam, Arizona location. Simulated streamflow from VIC simulation is driven by downscaled climate model forcings from Trace 44.

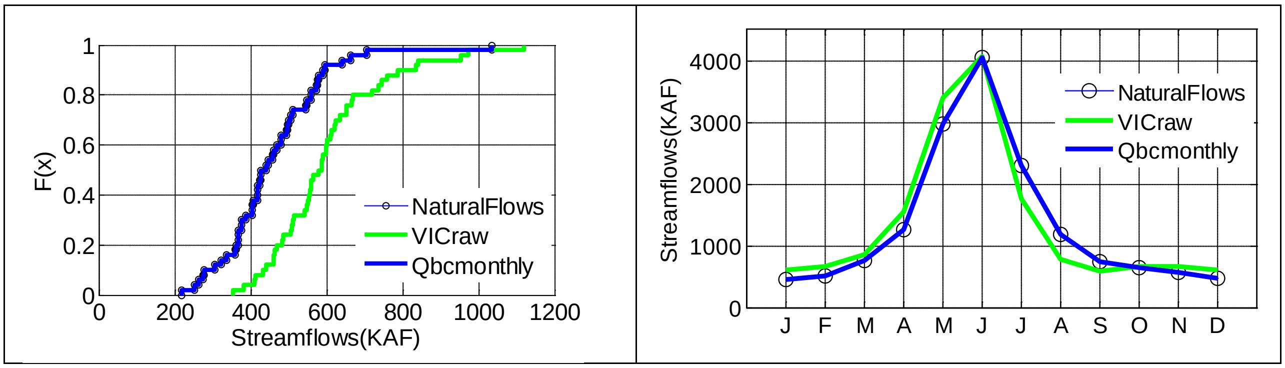


2. Develop a quantile map that aligns the observed CDF with the simulated CDF for each simulated month for the period 1950 to 1999 at each location. For each simulated value, determine the simulated percentile and adjust to be equal to the observed flow at the same percentile. This method preserves the mean and variance of the observed flows. See figure B4-7.

FIGURE B4-7

Comparisons of the January Cumulative Distribution Function (CDF) (left) and Mean Monthly (right) Streamflow Developed from VIC-simulated Streamflow, VIC Monthly Bias-Corrected, and Natural Streamflow

Colorado River at Parker Dam, Arizona location. Simulated streamflow from VIC simulation as driven by downscaled climate model forcings from Trace 44.

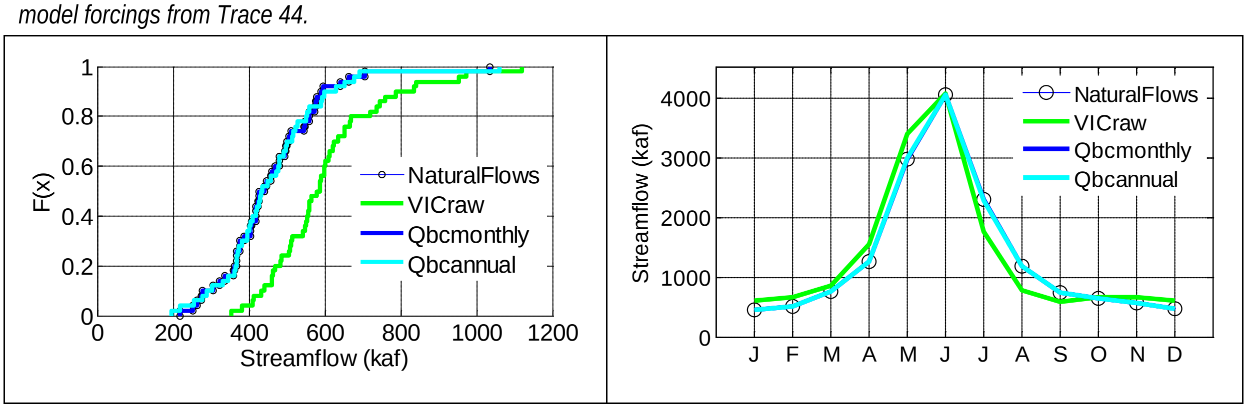


3. Re-scale the monthly values (if needed) to ensure that the annual simulated CDF aligns with the observed CDF. For each simulated annual flow value from step 2, determine the percentile and adjust to be equal to the observed flow at the same percentile. This step ensures that the adjusted streamflows are consistent at the annual scale. See figure B4-8.

FIGURE B4-8

Comparisons of the January Cumulative Distribution Function (CDF) (left) and Mean Monthly (right) Streamflow Developed from VIC-simulated Streamflow, VIC Monthly Bias-Corrected, VIC Annual Bias-Corrected, and Natural Streamflow

Colorado River at Parker Dam, Arizona location. Simulated streamflow from VIC simulation as driven by downscaled climate model forcings from Trace 44.



Because the bias correction is performed for each station independently, this can create discrepancies in spatial mass balance. Additional steps described below are performed to remove any spatial mass balance inconsistencies. The procedure begins from the most downstream location and moving upstream, as described below:

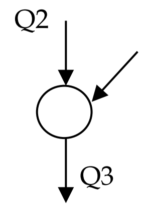
4. Anchor the calculations at the most downstream location (i.e., bias corrected streamflows at the Imperial Dam are unaltered).

5. Compare bias corrected flows at upstream locations (including incremental flows) with the downstream location. Compute the difference (Deltamon) as the downstream-computed monthly flow (Qds) minus the upstream-computed monthly flow (Qus), then adjust all upstream flows based on their relative flow contribution.

$$\mathrm{Delta}_{mon} = Q_{ds} - Q_{us} \text{ or (e.g. } Q3 - (Q1+Q2) \text{)}$$

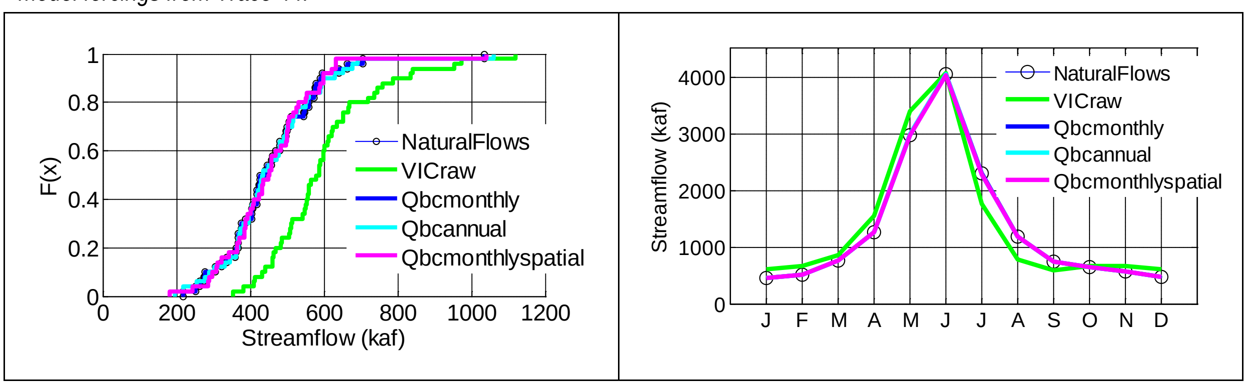
$$\mathrm{Adj}_{i,\ mon} = \mathrm{Delta}_{mon} * |Qi|/\mathrm{sum}(|Qi..n|) \text{ or}$$

$$[\text{e.g. Adj1,mon} = \text{Delta,mon} * |Q1|/(|Q1|+|Q2|)\ ]$$



This process results in consistent mass balance on monthly scales (i.e., $Q_3=Q_1+Q_2$). See figure B4-9.

FIGURE B4-9
Comparisons of the January Cumulative Distribution Function (CDF) (left) and Mean Monthly (right) Streamflow Developed from VIC-simulated Streamflow, VIC Monthly Bias-Corrected, VIC Annual Bias-Corrected, VIC Monthly Spatial Mass Balance Corrected and Natural Streamflow
Colorado River at Parker Dam, Arizona location. Simulated streamflow from VIC simulation as driven by downscaled climate model forcings from Trace 44.



4. Finally, a verification check is performed based on the annual flows to ensure that all mass balance and corrections have been implemented correctly. See figure B4-10.

A summary of the biases for each step in the bias correction process is shown for one climate projection simulation (table B4-2). The process is automated such that each Downscaled GCM Projection streamflow is bias corrected independently. The results from the VIC simulation presented in table B4-2 are different than those presented in table B4-1 because the VIC simulation is driven by two different meteorological datasets. Table B4-2 shows the results when simulated over the historical period with one GMC-simulated historical climate. The bias thus represents both hydrologic and meteorologic bias. The “station” bias correction column shows the resulting biases after conducting steps 1 through 3 in the streamflow bias correction above. The “spatial balance” bias correction column shows the resulting biases after conducting steps 1 through 6, and represents the final residual bias in the model results.

FIGURE B4-10
Comparisons of the January Cumulative Distribution Function (CDF) (left) and Mean Monthly (right) Streamflow Developed from VIC-simulated Streamflow, VIC Monthly Bias-Corrected, VIC Annual Bias-Corrected, VIC Monthly Spatial Mass Balance Corrected, VIC Annual Spatial Mass Balance Corrected, and Natural Streamflow
Colorado River at Parker Dam, Arizona location. Simulated streamflow from VIC simulation as driven by downscaled climate model forcings from Trace 44.

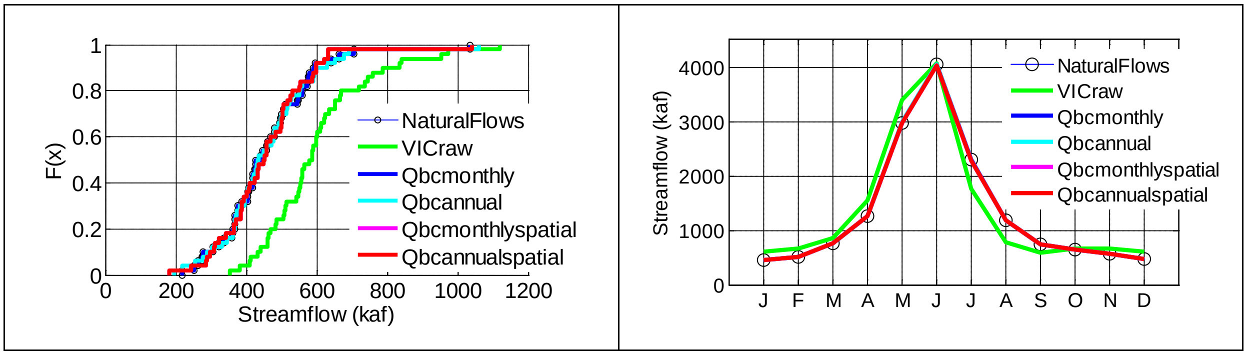


TABLE B4-2
Summary of Biases at the 20 Upper Basin Natural Flow Stations at Each Step in the Bias Correction Process

				% Differences of Streamflows		
ID	Location	Obs Nat Flow	VIC Nat Flow	% Bias	Station Bias-correction	Spatial Balance Bias-correction
Stn01	Colorado River at Glenwood Springs, CO	2,071	2,181	5.3%	0.0%	1.3%
Stn02	Colorado River near Cameo, CO	3,489	3,701	6.1%	0.0%	0.9%
Stn03	Taylor River below Taylor Park Reservoir, CO	148	174	17.0%	0.0%	2.4%
Stn04	Gunnision River at Blue Mesa Reservoir, CO	1,045	1,314	25.8%	0.0%	1.3%
Stn05	Gunnison River at Crystal Reservoir, CO	1,273	1,486	16.7%	0.0%	0.6%
Stn06	Gunnison River near Grand Junction, CO	2,304	2,293	-0.5%	0.0%	-0.3%
Stn07	Dolores River near Cisco, UT	789	537	-32.0%	0.0%	-2.5%
Stn08	Colorado River near Cisco UT	6,647	6,699	0.8%	0.0%	0.2%
Stn09	Green R Bel Fontenelle Res, WY	1,364	1,062	-22.1%	0.0%	2.1%
Stn10	Green R. near Green River, WY	1,469	1,198	-18.5%	0.0%	1.7%
Stn11	Green River near Greendale, UT	2,009	1,881	-6.4%	0.0%	1.6%
Stn12	Yampa River near Maybell, CO	1,210	1,078	-10.9%	0.0%	0.9%
Stn13	Little Snake River near Lily, CO	466	558	19.6%	0.0%	0.2%
Stn14	Duchesne River near Randlett, UT	778	872	12.1%	0.0%	1.3%
Stn15	White River near Watson, UT	557	516	-7.2%	0.0%	1.0%
Stn16	Green River at Green River, UT	5,397	5,234	-3.0%	0.0%	1.0%
Stn17	San Rafael River near Green River, UT	161	262	62.2%	0.0%	-1.3%
Stn18	San Juan River near Archuleta, NM	1,028	867	-15.7%	0.0%	-0.8%
Stn19	San Juan River near Bluff, UT	1,953	1,835	-6.0%	0.0%	-0.7%
Stn20	Colorado R at Lees Ferry, AZ	14,673	14,839	1.1%	0.0%	0.3%

5.0 VIC-simulated Hydrologic Fluxes

Although the primary result of the VIC modeling is streamflow for use in Colorado River system modeling, the model also produces hydrologic fluxes that are important in describing the causes of changes in streamflows. This section provides details on the methods and use of such hydrologic fluxes.

5.1 Climate and Gridded Hydrologic Process Analysis Methods

Gridded climate and hydrologic process data were generated by the VIC model for the historical and the 112 climate projection scenarios. These data were converted to a specialized format, allowing for statistical analysis and visualization via spatial mapping. This analysis was performed to better understand the primary factors, both climatological and hydrological, that drive projected changes in streamflows relative to historical conditions.

5.2 Production of Gridded Data Sets

In addition to streamflows, the VIC model exports climate and hydrologic data for each simulation. The climate data include average air temperature (degrees Celsius [°C]) generated during the model simulations and precipitation (millimeters [mm]), which is consistent with the data provided in the model input files. Hydrologic parameters include ET, runoff (surface runoff), baseflow (subsurface runoff), soil moisture (in each of three soil layers), and snow water equivalent (SWE). Both the climate and hydrologic data are stored in American Standard Code for Information Interchange-formatted text files known as "flux files." One flux file is produced for every grid cell of the Study Area, and each file contains values for the specified parameters at every time step of the simulation.

The flux file output generated by the VIC model was converted to network common data format (netCDF) to more readily evaluate and visualize the data. Developed by the staff at the Unidata Program Center in Boulder, Colorado, netCDF is a machine-independent data format for array-oriented (i.e., multi-dimensional) scientific data. In particular, netCDF is well suited to spatially gridded time series data, such as gridded climate data. Unidata has developed a variety of software libraries and tools that support the creation, manipulation, and analysis of multi-dimensional data. Unidata's netCDF-Java library was used to develop an application-specific Java program to convert the VIC flux files from American Standard Code for Information Interchange format to netCDF format.

The resulting netCDF files are each three-dimensional, defined by latitude, longitude, and time. The spatial extent of the hydrologic basin spans from latitude 31.3125° to 43.4375° North and from longitude 115.6875° to 105.6875° West. Given a grid cell size of 1/8th-degree, the latitude dimension spans 98 grid cells and the longitude dimension spans 81 grid cells, for a total 7,938 grid cells. The temporal extent of the data is from 1950 to 2099. Given a monthly time step, the time dimension consists of 1,800 values.

The complete list of parameters included in the netCDF files is as follows:

- Average air temperature (°C)
- Precipitation (mm)
- ET (mm)
- Potential ET (mm)
- ET Efficiency (percent)
- Runoff (surface) (mm)
- Baseflow (subsurface) (mm)
- Total Runoff (mm)
- Total Runoff Efficiency (percent)
- Soil Moisture Sum (mm)
- Maximum Soil Moisture (mm)
- Soil Moisture Fraction (percent)
- SWE (mm)

One netCDF file was produced for each climate projection and for the historic scenario, for a total of 113 netCDF files.

5.3 Statistical Analysis

To quantify potential changes between historical and future time periods, the VIC output data were statistically evaluated. For each historical and future time period of interest, statistics were developed for the consolidated dataset consisting of all 112 projections, such that the resulting statistics are representative of the 112-member ensemble. Statistics were generated for a subset of the VIC output parameters and derived parameters described previously. The eight parameters evaluated are as follows:

- Average air temperature (°C)
- Precipitation (mm)
- ET (mm)
- ET Efficiency (percent)
- Total Runoff (mm)
- Total Runoff Efficiency (percent)
- Soil Moisture Fraction (percent)
- SWE (mm)

A Java program was developed to process the VIC model output data stored in the netCDF files described previously. The Java program relies heavily on the netCDF-Java library, and on the Descriptive Statistics package of the Apache Commons math library. The statistics generated for each parameter include the mean, standard deviation, variance, skew, minimum, and maximum. In addition, the CDF for each time period was produced. A CDF describes the probability that a data point will be found at a value less than or equal to some value, "*x*." For this analysis, "*x*" values corresponding to all integer percentiles from 1 to 100 (inclusive) were generated for each cumulative distribution function.

5.3.1 Analysis Time Periods

Three future periods were selected for comparison to the historical period. Each period, including the historical, consists of 30 years and is identified by the representative middle value that defines that period. For example, the historical period consists of the years 1971 to 2000, and is represented by the year 1985. The historical period of 1971 to 2000 was selected as the reference climate because it was the established climate normal used by the National Oceanic and Atmospheric Administration at the onset of the Study. The three future periods selected for analysis were 2011 to 2040 (represented by the year 2025), 2041 to 2070 (represented by the year 2055), and 2066 to 2095 (represented by the year 2080). Because the last year of the climate projections is 2099, which is 1 year short of a 30-year period starting in 2071, the end year selected for the 2080 period was 2095. Therefore, the 2080 period includes 5 years of overlap (2066 to 2070) with the 2055 period. For each of the four time periods specified, the representative statistics described previously were generated on a monthly, seasonal, and annual basis. In this analysis, the seasons are defined as follows:

- Fall: October, November, and December
- Winter: January, February, and March
- Spring: April, May, and June
- Summer: July, August, and September

5.3.2 Analysis Spatial Scale

The statistical analysis described previously was conducted on both a grid cell and watershed basis. The results of the grid cell analysis produce the most informative map graphics and clearly show spatial variation at the greatest resolution possible. At this spatial scale, the statistics for each grid cell are developed independently.

In contrast, watershed statistics are developed concurrently for all grid cells that are members of a watershed unit. In this case, a time series of watershed data was generated for each parameter prior to conducting the statistical analysis. For a given watershed, this was done by averaging the values of all member grid cells for each time step of the simulation period. The statistical analysis was then applied to the watershed time series, such that the resulting values are representative of the watershed as a whole. The watershed analysis results in a more manageable set of outputs and is useful for evaluating trends in different regions of the basin.

5.3.3 Statistical Analysis Output

The resulting statistics were stored in four-dimensional netCDF files, which are defined by latitude, longitude, time, and statistic. The spatial extent of the Study Area spans from latitude 31.3125 ° to 43.4375 °North and from longitutde 115.6875 ° to 105.6875 °West. Given a grid cell size of 1/8th-degree, the latitude dimension spans 98 grid cells and the longitude dimension spans 81 grid cells, for a total 7,938 grid cells. The temporal extent of the data consisted of 17 values, each of which represents a monthly (1 to 12), annual (13), or seasonal (14 to 17) analysis time. The "statistic" dimension contains 111 values. The first 100 values are integer percentiles corresponding to the CDF distribution. The last 11 values represent the general statistics—mean, standard deviation, variance, skewness, minimum, P10, P25, P50, P75, P90, and maximum. Two netCDF files were produced for each of the four time periods—one for the grid cell-based statistics and one for the watershed-based statistics. Each netCDF file contains statistics representative of the 112-member projection ensemble for each of the eight climatological and hydrologic parameters identified previously. For watershed statistics, text files containing the general statistics and CDF values are also produced for each variable and time period. This output allows for ready production of spreadsheet charts, such as those presented in the results section.

5.3.4 Change Metrics

Finally, change metrics were generated for each parameter, in which the difference between future period statistics and historical period statistics were calculated on both absolute and percent change bases. These results are again stored in netCDF files, with two files generated for each future period—one for grid cell data and one for watershed data. The format of these files is identical to those containing the results of the statistical analysis.

6.0 VIC Model Limitations

The VIC model and simulations described in this appendix include several limitations that should be considered:

- Although the VIC model contains several sub-grid mechanisms, the coarse-grid scale should be noted when considering results and analysis of local-scale phenomenon. The VIC model is currently best applied for the regional scale hydrologic analyses.

- The VIC model has been applied without re-calibration. As the results suggest, the model is reasonable for capturing flow changes at the larger watersheds in the Basin, but has significant bias at smaller scales. The streamflow bias correction method corrects for much of the bias, but improved VIC calibration would limit the extent of these adjustments.
- The VIC model has been evaluated for monthly and annual time-scales, but daily results have not been assessed. Caution should be exercised with the use of any daily results due to issues related to daily weather generation of inputs, lack of hydrology model evaluation, and inherent limitations with climate bias correction for extreme events.
- The VIC model is only as good as its inputs. There are several limitations to long-term gridded meteorology related to data, spatial-temporal interpolation, and bias correction that should be considered. In addition, the inputs to the model do not include any transient trends in the vegetation or water management that may affect streamflows; they should only be analyzed from a naturalized flow change standpoint.
- Finally, the VIC model includes three soil zones to capture the vertical movement of soil moisture, but does not include groundwater. In areas where groundwater connectivity with surface process or streamflow is important, the VIC model may not have sufficient subsurface characterization to capture hydrologic responses.

7.0 References

Brekke, L.D., M.D. Dettinger, E.P. Maurer, and M. Anderson. 2008. “Significance of Model Credibility in Estimating Climate Projection Distributions for Regional Hydroclimatological Risk Assessments.” *Climatic Change* Vol. 89 No. 3-4, 371-394, DOI: 10.1007/s10584-007-9388-3.

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.” Proceedings of the National Academy of Sciences, 107(50), 21271-21276, DOI: 10.1073/pnas.0912391107.

CH2M HILL. 2008. *Climate Change Study, Report on Evaluation Methods and Climate Scenarios*.

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.” *Hydrology and Earth System Sciences*, 11, 1417–1434.

Hamlet, A.F., P. Carrasco, J. Deems, M.M. Elsner, T. Kamstra, C. Lee, S-Y Lee, G. Mauger, E. P. Salathé, I. Tohver, and L. Whitely Binder. 2010. *Final Project Report for the Columbia Basin Climate Change Scenarios Project*. Retrieved from http://www.hydro.washington.edu/2860/report/.

Liang, X., D.P. Lettenmaier, E.F. Wood , and S.J. Burges. 1994. “A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models.” *Journal of Geophysical Research*, Vol. 99, pp. 14415-14428.

Liang, X., D.P. Lettenmaier, and E.F. Wood . 1996. *Surface Soil Moisture Parameterization of the VIC-2L Model: Evaluation and Modification.*

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15(22), 3237-3251.

Appendix B5
Supplemental Streamflow Analysis

Appendix B5 — Supplemental Streamflow Analysis

The streamflow analyses presented in this appendix provide additional supporting information consistent with that provided in the Technical Report. The streamflow analysis, as described here, was based on reconstructed natural flows in the Colorado River Basin (Basin). The data consist of two historical datasets. The first dataset (referred to as the observed record) consists of monthly observed natural flows for the period October 1905 to September 2007. The second dataset (referred as the paleo record) consists of monthly flows reconstructed from tree ring analysis for the period October 761 to September 2005.

The observed record was provided in the total flows format (flows accumulating from upstream to downstream locations) and intervening format (single watershed flows). The paleo record was provided in an intervening format and had to be accumulated from upstream to downstream basins to obtain a total flows format.

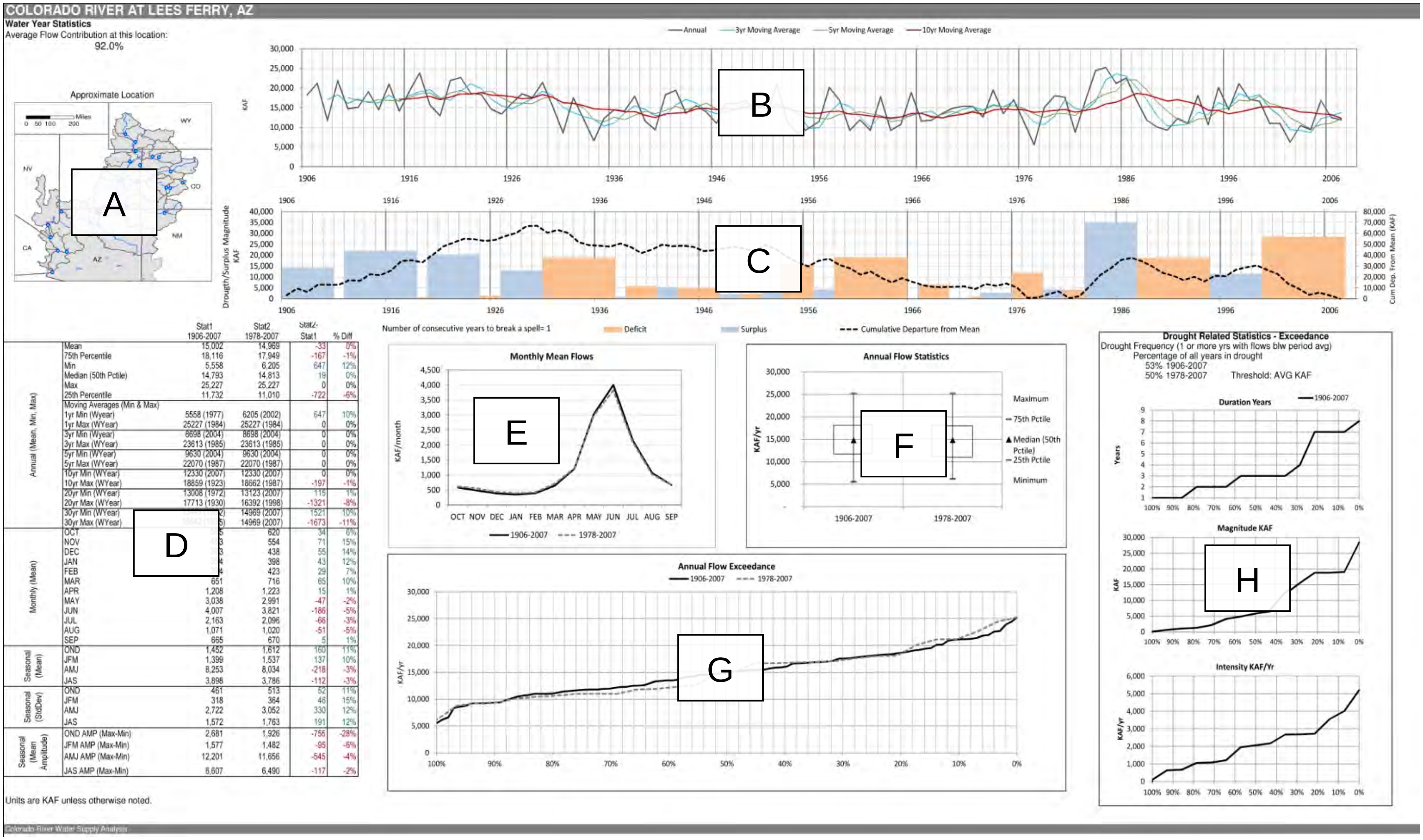
1.0 Streamflow Data Summary

Streamflow was analyzed for the 29 natural flow stations that serve as the primary inflow locations for the Colorado River Simulation System model. A spreadsheet tool was constructed to provide an interactive environment to explore the temporal and spatial characteristics of streamflow in the Basin, as shown in figure B5-1. The features of this visual summary are described as follows:

A. Table of Statistics: The table includes statistics (Stat1 and Stat2) for two periods in columns that represent the absolute and percentage difference between the two time periods. The Stat1 and Stat2 columns present the long-term water year streamflow average for the two periods. The "Annual" statistic block shows the minimum and the maximum observed for the 1-year totals and 3-, 5-, 10-, 20-, and 30-year moving averages, followed by the year that the value was observed (e.g., the line "3yr Min (WYear) 7370 (1847)" represents a minimum value of 7,370 thousand acre-feet (kaf) per year for a 3-year moving average time series ending in the year of 1847). The "Monthly statistics" section shows the monthly streamflow averages for each month, followed by the seasonal statistics (average, standard deviation, and amplitude [maximum-minimum]). The amplitude accounts for all seasons; for example, for amplitude October, November, and December (OND), the value on the table is computed as the maximum flow observed in an OND season minus the minimum flow observed in an OND season. The minimum and the maximum do not necessarily occur in the same water year.

B. Average Monthly Streamflow Graphic: Average monthly streamflow (kaf) is shown for the water year over the time periods. The data used for this plot are also presented in the Table of Statistics as Stat1 (solid line) and Stat2 (dashed line). This graphic can be used to assess monthly and seasonal shifts in streamflow from the comparison periods.

FIGURE B5-1
Summary Graphic for Colorado River at Lees Ferry, Arizona Displaying Streamflow, Annual Exceedance Probabilities, Streamflow Deficits and Surpluses, and Drought Duration, Magnitude and Intensity



		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	15,002	14,969	-33	0%
	75th Percentile	18,116	17,949	-167	-1%
	Min	5,558	6,205	647	12%
	Median (50th Pctile)	14,793	14,813	19	0%
	Max	25,227	25,227	0	0%
	25th Percentile	11,732	11,010	-722	-6%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	5558 (1977)	6205 (2002)	647	10%
	1yr Max (WYear)	25227 (1984)	25227 (1984)	0	0%
	3yr Min (Wyear)	8698 (2004)	8698 (2004)	0	0%
	3yr Max (WYear)	23613 (1985)	23613 (1985)	0	0%
	5yr Min (WYear)	9630 (2004)	9630 (2004)	0	0%
	5yr Max (WYear)	22070 (1987)	22070 (1987)	0	0%
	10yr Min (WYear)	12330 (2007)	12330 (2007)	0	0%
	10yr Max (WYear)	18859 (1923)	18662 (1987)	-197	-1%
	20yr Min (WYear)	13008 (1972)	13123 (2007)	115	1%
	20yr Max (WYear)	17713 (1930)	16392 (1998)	-1321	-8%
	30yr Min (WYear)	[illegible]	14969 (2007)	1521	10%
	30yr Max (WYear)	[illegible]	14969 (2007)	-1673	-11%
Monthly (Mean)	OCT	[illegible]	620	34	6%
	NOV	[illegible]	554	71	15%
	DEC	[illegible]	438	55	14%
	JAN	[illegible]	398	43	12%
	FEB	[illegible]	423	29	7%
	MAR	651	716	65	10%
	APR	1,208	1,223	15	1%
	MAY	3,038	2,991	-47	-2%
	JUN	4,007	3,821	-186	-5%
	JUL	2,163	2,096	-66	-3%
	AUG	1,071	1,020	-51	-5%
	SEP	665	670	5	1%
Seasonal (Mean)	OND	1,452	1,612	160	11%
	JFM	1,399	1,537	137	10%
	AMJ	8,253	8,034	-218	-3%
	JAS	3,898	3,786	-112	-3%
Seasonal (StdDev)	OND	461	513	52	11%
	JFM	318	364	46	15%
	AMJ	2,722	3,052	330	12%
	JAS	1,572	1,763	191	12%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	2,681	1,926	-755	-28%
	JFM AMP (Max-Min)	1,577	1,482	-95	-6%
	AMJ AMP (Max-Min)	12,201	11,656	-545	-4%
	JAS AMP (Max-Min)	6,607	6,490	-117	-2%

Units are KAF unless otherwise noted.

C. Annual Streamflow Box and Whiskers Graphic: This plot illustrates annual streamflow variability for the two time periods. The box represents the range of half of annual observed flows (inter-quartile range between 25th and 75th percentile). The triangle represents the median, and the horizontal lines at the top of the vertical line represent the period of record maximum and minimum annual values. This graphic can be used to assess trends in period streamflow variability and volumes.

D. Table of Statistics: The table includes statistics (Stat1 and Stat2) for two periods in columns that represent the absolute and percentage difference between the two time periods. The Stat1 and Stat2 columns present the long-term water year streamflow average for the two periods. The "Annual" statistic block shows the minimum and the maximum observed for the 1-year totals and 3-, 5-, 10-, 20-, and 30-year moving averages, followed by the year that the value was observed (e.g., the line "3yr Min (WYear) 7370 (1847)" represents a minimum value of 7,370 kaf per year for a 3-year moving average time series ending in the year of 1847). The "Monthly statistics" section shows the monthly streamflow averages for each month, followed by the seasonal statistics (average, standard deviation, and amplitude [maximum-minimum]). The amplitude accounts for all seasons; for example, for amplitude October, November, and December (OND), the value on the table is computed as the maximum flow observed in an OND season minus the minimum flow observed in an OND season. The minimum and the maximum do not necessarily occur in the same water year.

E. Average Monthly Streamflow Graphic: Average monthly streamflow (kaf) is shown for the water year over the time periods. The data used for this plot are also presented in the Table of Statistics as Stat1 (solid line) and Stat2 (dashed line). This graphic can be used to assess monthly and seasonal shifts in streamflow from the comparison periods.

F. Annual Streamflow Box and Whiskers Graphic: This plot illustrates annual streamflow variability for the two time periods. The box represents the range of half of annual observed flows (inter-quartile range between 25th and 75th percentile). The triangle represents the median, and the horizontal lines at the top of the vertical line represent the period of record maximum and minimum annual values. This graphic can be used to assess trends in period streamflow variability and volumes.

G. Annual Streamflow Exceedance Graphic: This plot presents the full range of probabilities of exceeding a given streamflow for two selected periods. The plot is equivalent to the box and whiskers plot but provides probabilities ranging from zero to 100 percent. This graphic can be used to assess trends in period streamflow variability and volumes. For example, at the Lees Ferry, Arizona, location, 90 percent of the years had streamflows exceeding 10,000 kaf for both periods.

H. Deficit Related Statistics – Exceedance Plots: The deficit statistics are illustrated in three charts: duration, magnitude, and intensity. The statistics presented in these charts refer only to deficit periods defined as only the years when streamflows were below the specified threshold. The "percentage of all years in a deficit" takes into account all years in the time period and determines how many were within a "deficit." Below is a more detailed description of the deficit related statistics.

The average streamflow for each time period is the default threshold to define deficit or surplus periods (e.g., a sequence of years with streamflows below the average is considered a deficit period).

Duration: The duration chart presents the exceedance probability of deficit duration in years. For example, the chart illustrates that at Lees Ferry, 30 percent of the years defined as deficit years (only deficit years) had a deficit that lasted or exceeded 3 years in duration.

Magnitude: The magnitude of a deficit (kaf) corresponds to the cumulative difference between observed streamflows and long-term average streamflows for an uninterrupted drought period. The exceedance plot shows the probability of a deficit to exceed a certain magnitude based on observed flows.

Intensity: Deficit intensity is presented as magnitude divided by duration. The chart presents the exceedance probabilities for two selected periods.

2.0 Streamflow Data Summaries

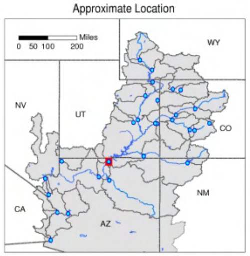
Sample streamflow data summaries are provided in the following pages for the following natural flow stations:

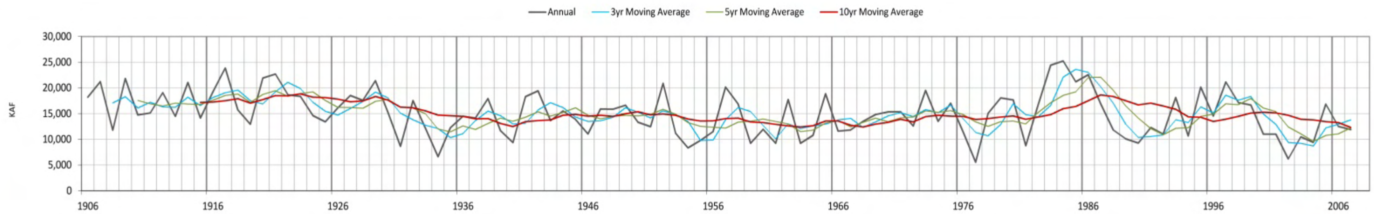
- Figure B5-2: Colorado River at Lees Ferry, Arizona (Station 20)
- Figure B5-3: Green River at Green River, Utah (Station 16)
- Figure B5-4: Colorado River near Cisco, Utah (Station 8)
- Figure B5-5: San Juan River near Bluff, Utah (Station 19)
- Figure B5-6: Colorado River above Imperial Dam, Arizona (Station 29)

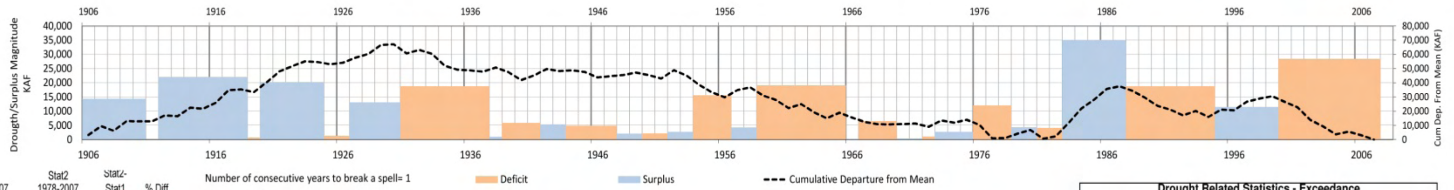
FIGURE B5-2
Streamflow Data Summary for Colorado River at Lees Ferry, Arizona, Natural Flows
Based on historical 1906–2007 data.

COLORADO RIVER AT LEES FERRY, AZ

Water Year Statistics
Average Flow Contribution at this location:
92.0%

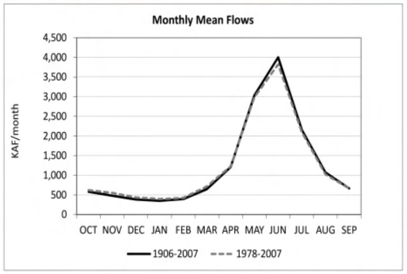


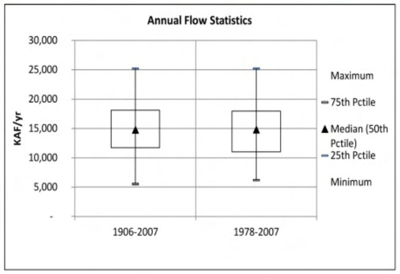


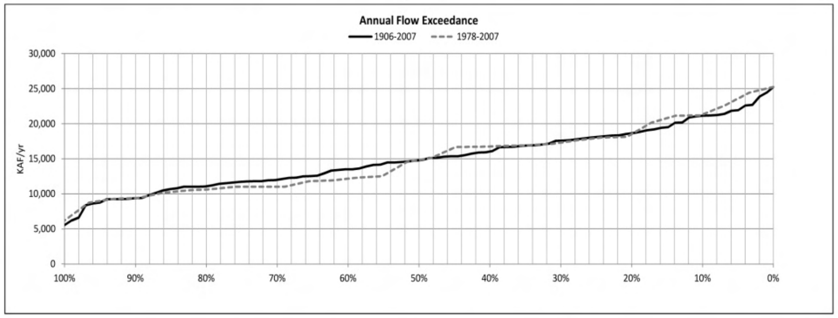


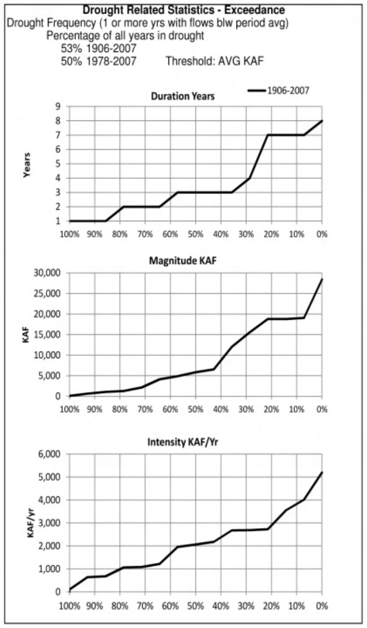
		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	15,002	14,969	-33	0%
	75th Percentile	18,116	17,949	-167	-1%
	Min	5,558	6,205	647	12%
	Median (50th Pctile)	14,793	14,813	19	0%
	Max	25,227	25,227	0	0%
	25th Percentile	11,732	11,010	-722	-6%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	5558 (1977)	6205 (2002)	647	10%
	1yr Max (WYear)	25227 (1984)	25227 (1984)	0	0%
	3yr Min (Wyear)	8698 (2004)	8698 (2004)	0	0%
	3yr Max (WYear)	23613 (1985)	23613 (1985)	0	0%
	5yr Min (WYear)	9630 (2004)	9630 (2004)	0	0%
	5yr Max (WYear)	22070 (1987)	22070 (1987)	0	0%
	10yr Min (WYear)	12330 (2007)	12330 (2007)	0	0%
	10yr Max (WYear)	18859 (1923)	18662 (1987)	-197	-1%
	20yr Min (WYear)	13008 (1972)	13123 (2007)	115	1%
	20yr Max (WYear)	17713 (1930)	16392 (1998)	-1321	-8%
	30yr Min (WYear)	13449 (1982)	14969 (2007)	1521	10%
	30yr Max (WYear)	16642 (1935)	14969 (2007)	-1673	-11%
Monthly (Mean)	OCT	585	620	34	6%
	NOV	483	554	71	15%
	DEC	383	438	55	14%
	JAN	354	398	43	12%
	FEB	394	423	29	7%
	MAR	651	716	65	10%
	APR	1,208	1,223	15	1%
	MAY	3,038	2,991	-47	-2%
	JUN	4,007	3,821	-186	-5%
	JUL	2,163	2,096	-66	-3%
	AUG	1,071	1,020	-51	-5%
	SEP	665	670	5	1%
Seasonal (Mean)	OND	1,452	1,612	160	11%
	JFM	1,399	1,537	137	10%
	AMJ	8,253	8,034	-218	-3%
	JAS	3,898	3,786	-112	-3%
Seasonal (StdDev)	OND	461	513	52	11%
	JFM	318	364	46	15%
	AMJ	2,722	3,052	330	12%
	JAS	1,572	1,763	191	12%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	2,681	1,926	-755	-28%
	JFM AMP (Max-Min)	1,577	1,482	-95	-6%
	AMJ AMP (Max-Min)	12,201	11,656	-545	-4%
	JAS AMP (Max-Min)	6,607	6,490	-117	-2%

Units are KAF unless otherwise noted.







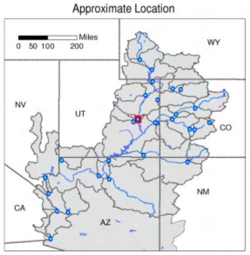


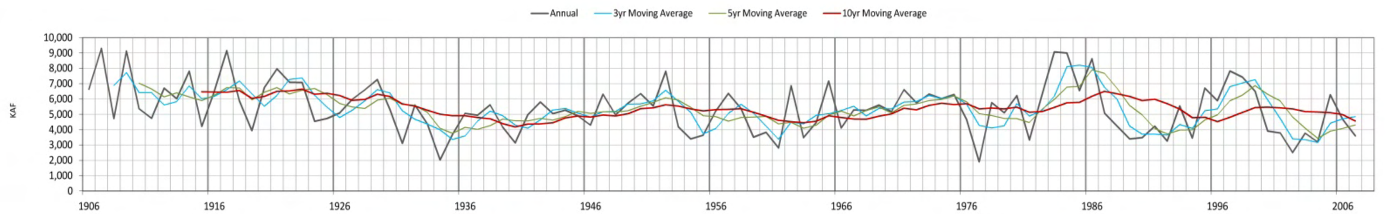
Colorado River Water Supply Analysis

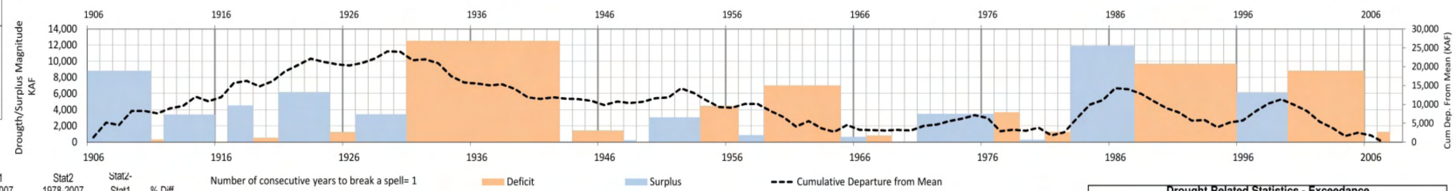
FIGURE B5-3
Streamflow Data Summary for Green River at Green River, Utah, Natural Flows
Based on historical 1906–2007 data.

GREEN RIVER AT GREEN RIVER, UT

Water Year Statistics
Average Flow Contribution at this location:
33.0%

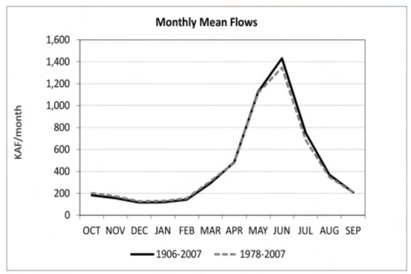


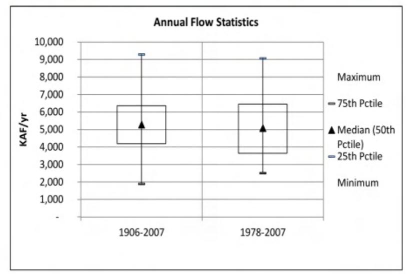


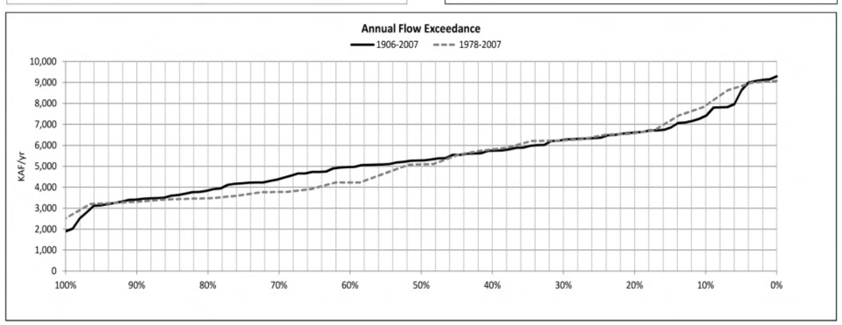


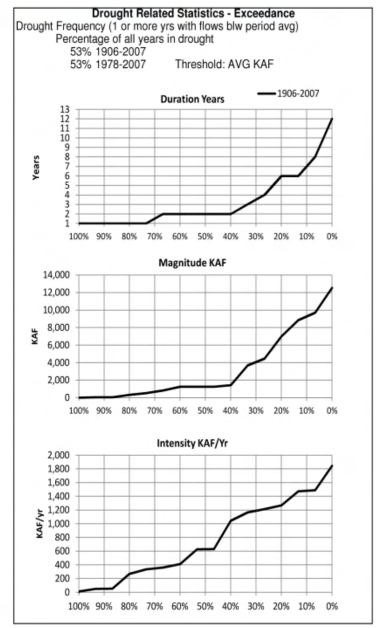
		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	5,385	5,288	-97	-2%
	75th Percentile	6,360	6,451	91	1%
	Min	1,903	2,515	612	32%
	Median (50th Pctile)	5,284	5,091	-193	-4%
	Max	9,297	9,076	-221	-2%
	25th Percentile	4,192	3,642	-550	-13%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	1903 (1977)	2515 (2002)	612	24%
	1yr Max (WYear)	9297 (1907)	9076 (1983)	-221	-2%
	3yr Min (Wyear)	3161 (2004)	3161 (2004)	0	0%
	3yr Max (WYear)	8210 (1985)	8210 (1985)	0	0%
	5yr Min (WYear)	3434 (2004)	3434 (2004)	0	0%
	5yr Max (WYear)	7897 (1986)	7897 (1986)	0	0%
	10yr Min (WYear)	4174 (1940)	4528 (1996)	354	8%
	10yr Max (WYear)	6639 (1923)	6497 (1987)	-142	-2%
	20yr Min (WYear)	4684 (2007)	4684 (2007)	0	0%
	20yr Max (WYear)	6417 (1925)	5803 (1999)	-614	-11%
	30yr Min (WYear)	4800 (1961)	5288 (2007)	489	9%
	30yr Max (WYear)	5913 (1935)	5288 (2007)	-625	-12%
Monthly (Mean)	OCT	183	202	18	10%
	NOV	156	172	16	10%
	DEC	117	127	9	8%
	JAN	120	131	11	10%
	FEB	142	155	13	9%
	MAR	292	312	20	7%
	APR	485	478	-6	-1%
	MAY	1,127	1,118	-10	-1%
	JUN	1,432	1,348	-84	-6%
	JUL	751	687	-65	-9%
	AUG	370	349	-21	-6%
	SEP	208	210	2	1%
Seasonal (Mean)	OND	457	501	43	9%
	JFM	554	598	44	8%
	AMJ	3,044	2,944	-100	-3%
	JAS	1,330	1,246	-84	-6%
Seasonal (StdDev)	OND	146	190	44	30%
	JFM	148	146	-1	-1%
	AMJ	1,049	1,184	135	13%
	JAS	547	563	16	3%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	774	638	-136	-18%
	JFM AMP (Max-Min)	712	607	-105	-15%
	AMJ AMP (Max-Min)	4,560	3,996	-563	-12%
	JAS AMP (Max-Min)	2,744	1,943	-802	-29%

Units are KAF unless otherwise noted.







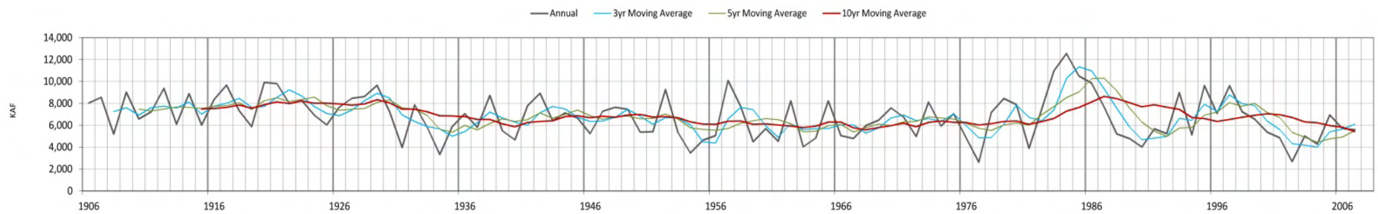


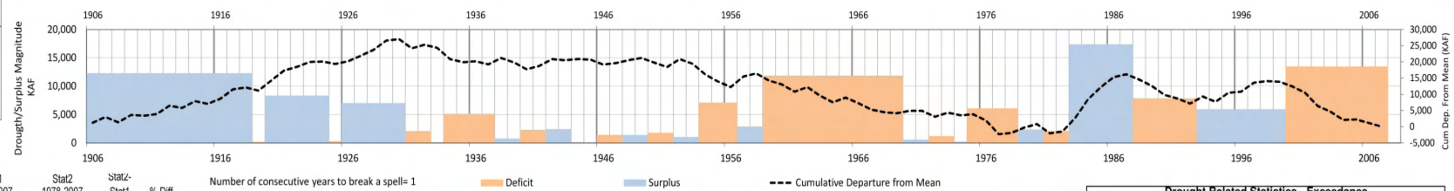
Colorado River Water Supply Analysis

FIGURE B5-4
Streamflow Data Summary for Colorado River near Cisco, Utah, Natural Flows
Based on historical 1906–2007 data.

COLORADO RIVER NEAR CISCO, UT

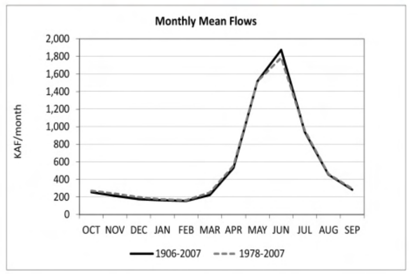
Water Year Statistics
Average Flow Contribution at this location:
41.6%

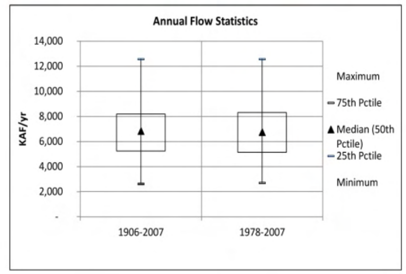


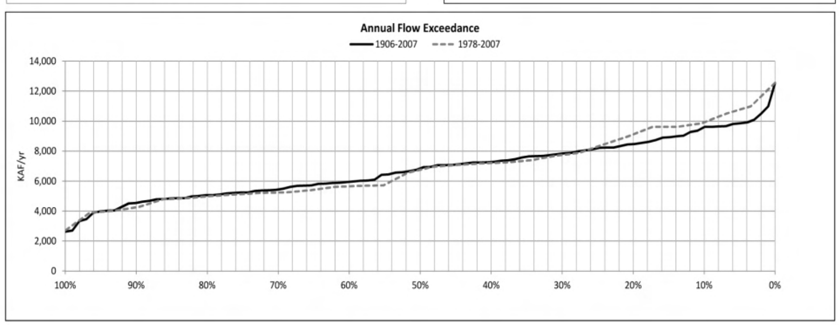


		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	6,793	6,869	76	1%
	75th Percentile	8,196	8,306	111	1%
	Min	2,625	2,702	77	3%
	Median (50th Pctile)	6,842	6,759	-83	-1%
	Max	12,561	12,561	0	0%
	25th Percentile	5,241	5,140	-101	-2%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	2625 (1977)	2702 (2002)	77	3%
	1yr Max (WYear)	12561 (1984)	12561 (1984)	0	0%
	3yr Min (Wyear)	3996 (2004)	3996 (2004)	0	0%
	3yr Max (WYear)	11347 (1985)	11347 (1985)	0	0%
	5yr Min (WYear)	4448 (2004)	4448 (2004)	0	0%
	5yr Max (WYear)	10314 (1987)	10314 (1987)	0	0%
	10yr Min (WYear)	5431 (2007)	5431 (2007)	0	0%
	10yr Max (WYear)	8636 (1987)	8636 (1987)	0	0%
	20yr Min (WYear)	5875 (1978)	5985 (2007)	110	2%
	20yr Max (WYear)	7972 (1930)	7590 (1998)	-382	-5%
	30yr Min (WYear)	6046 (1978)	6869 (2007)	823	12%
	30yr Max (WYear)	7457 (1935)	6869 (2007)	-589	-9%
Monthly (Mean)	OCT	255	271	16	6%
	NOV	214	240	26	12%
	DEC	178	198	20	11%
	JAN	163	175	12	7%
	FEB	157	164	7	5%
	MAR	224	253	29	13%
	APR	533	556	24	4%
	MAY	1,516	1,517	1	0%
	JUN	1,875	1,786	-90	-5%
	JUL	940	954	14	2%
	AUG	455	462	7	2%
	SEP	283	293	10	3%
Seasonal (Mean)	OND	646	709	62	10%
	JFM	544	591	48	9%
	AMJ	3,924	3,859	-65	-2%
	JAS	1,678	1,710	31	2%
Seasonal (StdDev)	OND	161	197	36	22%
	JFM	106	138	32	30%
	AMJ	1,317	1,571	255	19%
	JAS	665	788	123	18%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	845	740	-105	-12%
	JFM AMP (Max-Min)	611	590	-21	-3%
	AMJ AMP (Max-Min)	6,563	6,495	-68	-1%
	JAS AMP (Max-Min)	3,154	3,071	-83	-3%

Units are KAF unless otherwise noted.







Drought Related Statistics - Exceedance
Drought Frequency (1 or more yrs with flows blw period avg)
Percentage of all years in drought
49% 1906-2007
50% 1978-2007 Threshold: AVG KAF

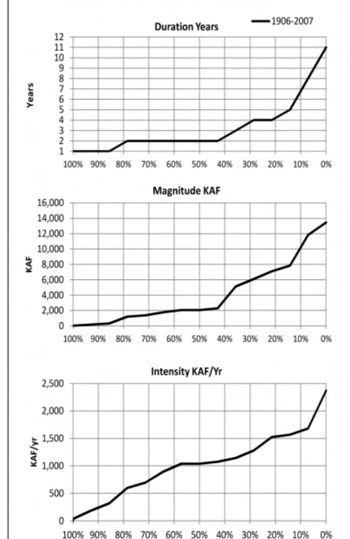
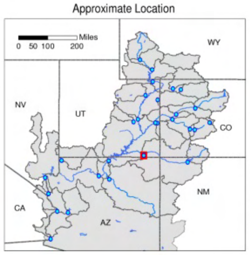
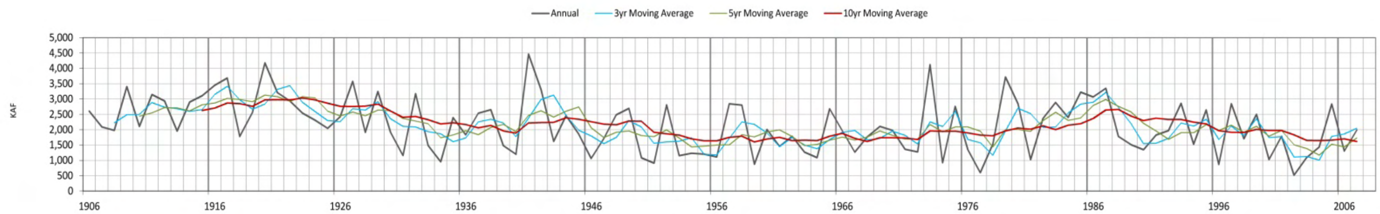


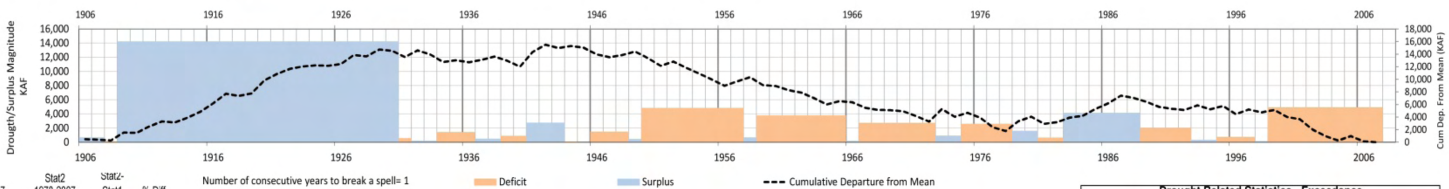
FIGURE B5-5
Streamflow Data Summary for San Juan River near Bluff, Utah, Natural Flows
Based on historical 1906–2007 data.

SAN JUAN RIVER NEAR BLUFF, UT

Water Year Statistics
Average Flow Contribution at this location:
13.1%

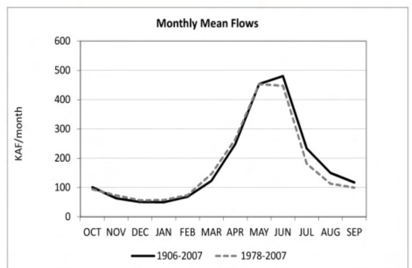


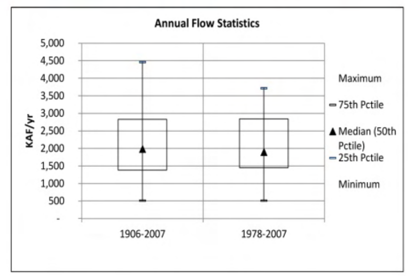


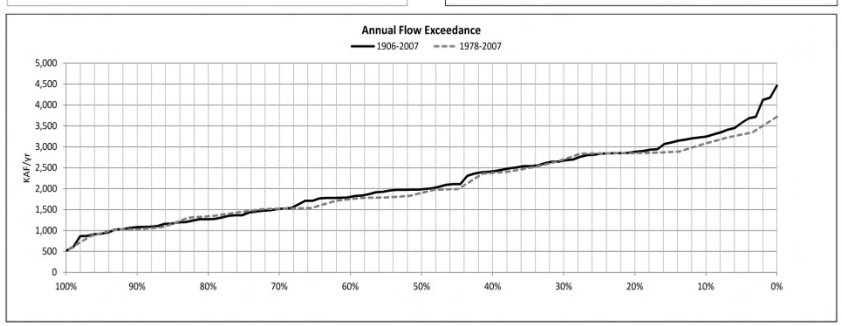


		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	2,139	2,060	-79	-4%
	75th Percentile	2,830	2,841	11	0%
	Min	514	514	0	0%
	Median (50th Pctile)	1,987	1,899	-87	-4%
	Max	4,466	3,718	-748	-17%
	25th Percentile	1,380	1,451	71	5%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	514 (2002)	514 (2002)	0	0%
	1yr Max (WYear)	4466 (1941)	3718 (1979)	-748	-20%
	3yr Min (Wyear)	1011 (2004)	1011 (2004)	0	0%
	3yr Max (WYear)	3438 (1922)	3214 (1987)	-223	-7%
	5yr Min (WYear)	1170 (2004)	1170 (2004)	0	0%
	5yr Max (WYear)	3127 (1920)	2986 (1987)	-141	-5%
	10yr Min (WYear)	1603 (1959)	1620 (2007)	17	1%
	10yr Max (WYear)	3032 (1923)	2666 (1988)	-366	-14%
	20yr Min (WYear)	1663 (1972)	1769 (2007)	106	6%
	20yr Max (WYear)	2811 (1927)	2288 (1998)	-522	-23%
	30yr Min (WYear)	1732 (1972)	2060 (2007)	328	16%
	30yr Max (WYear)	2584 (1938)	2060 (2007)	-524	-25%
Monthly (Mean)	OCT	101	94	-7	-7%
	NOV	64	73	10	15%
	DEC	51	57	6	12%
	JAN	50	58	8	15%
	FEB	69	74	5	8%
	MAR	123	146	23	19%
	APR	248	264	16	7%
	MAY	453	453	0	0%
	JUN	481	447	-34	-7%
	JUL	233	181	-52	-22%
	AUG	150	113	-36	-24%
	SEP	117	99	-18	-15%
Seasonal (Mean)	OND	216	224	9	4%
	JFM	242	278	36	15%
	AMJ	1,182	1,164	-18	-2%
	JAS	500	394	-106	-21%
Seasonal (StdDev)	OND	139	106	-33	-24%
	JFM	111	127	16	14%
	AMJ	548	561	13	2%
	JAS	288	219	-69	-24%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	886	522	-364	-41%
	JFM AMP (Max-Min)	472	435	-37	-8%
	AMJ AMP (Max-Min)	2,631	2,440	-190	-7%
	JAS AMP (Max-Min)	1,349	872	-476	-35%

Units are KAF unless otherwise noted.







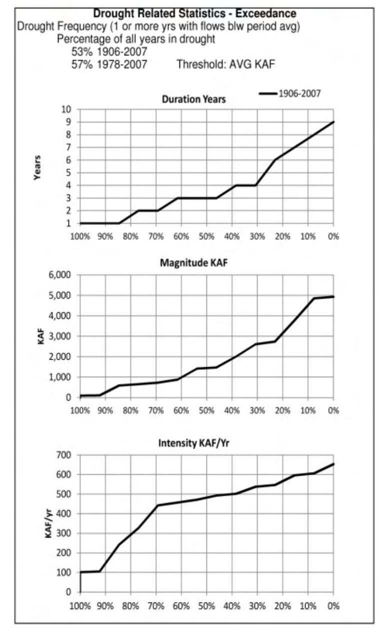
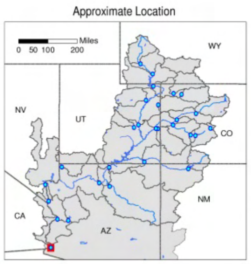
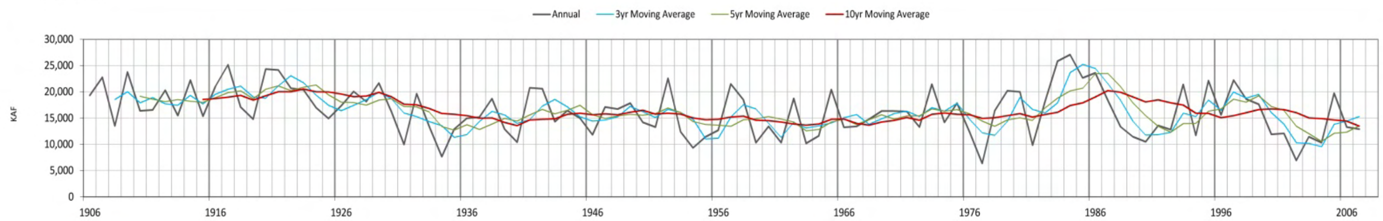


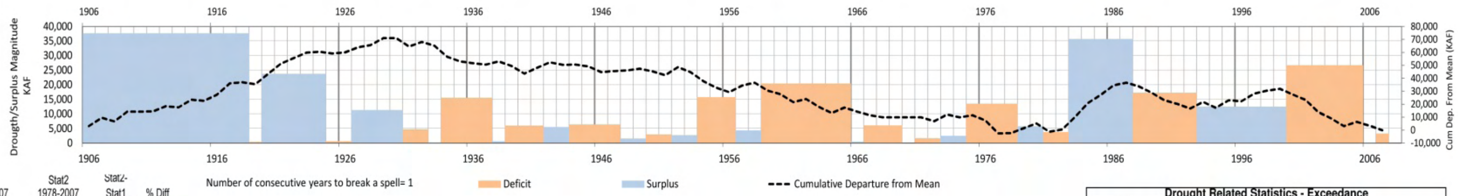
FIGURE B5-6
Streamflow Data Summary for Colorado River above Imperial Dam, Arizona, Natural Flows
Based on historical 1906–2007 data.

COLORADO RIVER ABOVE IMPERIAL DAM, AZ-CA

Water Year Statistics
Average Flow Contribution at this location:
100.0%

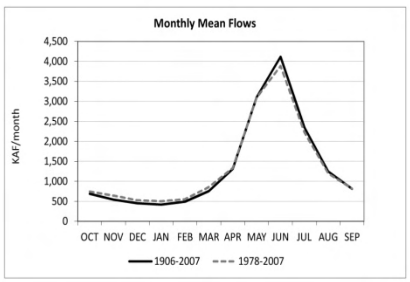


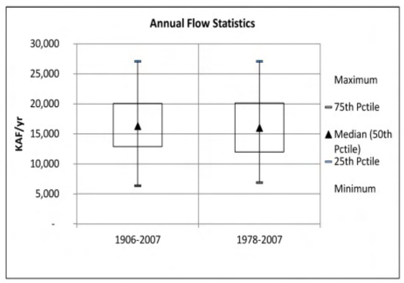


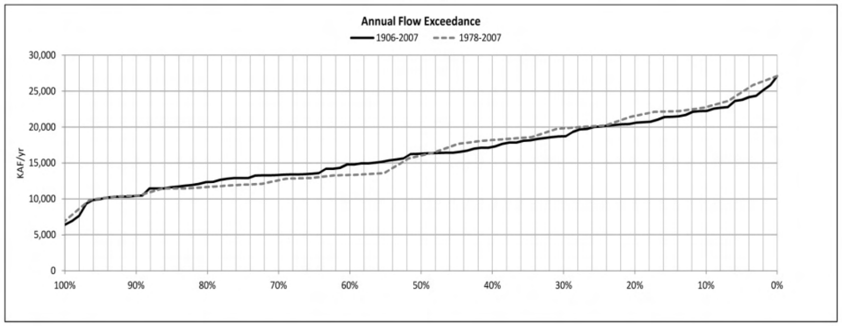


		Stat1 1906-2007	Stat2 1978-2007	Stat2-Stat1	% Diff
Annual (Mean, Min, Max)	Mean	16,311	16,394	83	1%
	75th Percentile	20,058	20,154	96	0%
	Min	6,377	6,914	536	8%
	Median (50th Pctile)	16,311	16,035	-276	-2%
	Max	27,090	27,090	0	0%
	25th Percentile	12,899	11,968	-931	-7%
	Moving Averages (Min & Max)				
	1yr Min (Wyear)	6377 (1977)	6914 (2002)	536	8%
	1yr Max (WYear)	27090 (1984)	27090 (1984)	0	0%
	3yr Min (Wyear)	9562 (2004)	9562 (2004)	0	0%
	3yr Max (WYear)	25199 (1985)	25199 (1985)	0	0%
	5yr Min (WYear)	10542 (2004)	10542 (2004)	0	0%
	5yr Max (WYear)	23513 (1987)	23513 (1987)	0	0%
	10yr Min (WYear)	13487 (2007)	13487 (2007)	0	0%
	10yr Max (WYear)	20524 (1923)	20215 (1987)	-309	-2%
	20yr Min (WYear)	14224 (1972)	14484 (2007)	260	2%
	20yr Max (WYear)	19265 (1925)	17956 (1998)	-1309	-7%
	30yr Min (WYear)	14700 (1978)	16394 (2007)	1694	10%
	30yr Max (WYear)	18080 (1935)	16394 (2007)	-1686	-10%
Monthly (Mean)	OCT	691	746	55	8%
	NOV	543	642	99	18%
	DEC	455	526	71	16%
	JAN	417	503	85	20%
	FEB	495	555	61	12%
	MAR	756	857	102	13%
	APR	1,312	1,335	23	2%
	MAY	3,109	3,098	-11	0%
	JUN	4,118	3,886	-232	-6%
	JUL	2,355	2,226	-129	-5%
	AUG	1,249	1,199	-50	-4%
	SEP	812	821	9	1%
Seasonal (Mean)	OND	1,688	1,914	226	13%
	JFM	1,667	1,915	248	15%
	AMJ	8,539	8,319	-220	-3%
	JAS	4,417	4,246	-170	-4%
Seasonal (StdDev)	OND	515	533	19	4%
	JFM	501	612	111	22%
	AMJ	2,786	3,105	319	11%
	JAS	1,619	1,808	189	12%
Seasonal (Mean Amplitude)	OND AMP (Max-Min)	2,491	1,937	-555	-22%
	JFM AMP (Max-Min)	2,892	2,646	-246	-8%
	AMJ AMP (Max-Min)	12,745	11,802	-943	-7%
	JAS AMP (Max-Min)	6,893	6,694	-199	-3%

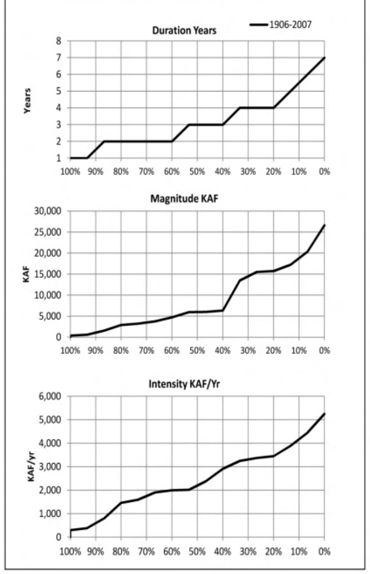
Units are KAF unless otherwise noted.







Drought Related Statistics - Exceedance
Drought Frequency (1 or more yrs with flows blw period avg)
Percentage of all years in drought
50% 1906-2007
50% 1978-2007 Threshold: AVG KAF



Colorado River Water Supply Analysis

Appendix B6
Watershed-based Climate and Hydrologic Process Changes

Appendix B6 — Watershed-based Climate and Hydrologic Process Changes

The results of the watershed-based statistical analysis of the Variable Infiltration Capacity model output (climatological and hydrologic parameters) are presented for a subset of the Colorado River Basin (Basin) watersheds. The selected watersheds span the geographic range of the Basin. One group of watersheds was selected from the Upper Basin, and each of these watersheds contains the headwaters of a significant river. A second group of watersheds was selected from the Lower Basin, and each contains a streamflow station of significance. The selected watersheds are as follows:

Upper Basin

- 01 – Colorado River at Glenwood Springs, Colorado
- 04 – Gunnison River at Blue Mesa Reservoir, Colorado
- 09 – Green River below Fontenelle Reservoir, Wyoming
- 12 – Yampa River near Maybell, Colorado
- 13 – Little Snake River near Lily, Colorado
- 18 – San Juan River near Archuletta, New Mexico
- 20 – Colorado River at Lees Ferry, Arizona

Lower Basin

- 25 – Colorado River below Hoover Dam, Arizona-Nevada
- 29 – Colorado River Above Imperial Dam, Arizona

Figures B6-1 through B6-9 depict the relative changes in monthly precipitation, temperature, evapotranspiration, runoff, snow water equivalent, and soil moisture for these selected watersheds. Separate lines depict the changes for the periods 2011 to 2040 (2025), 2041 to 2070 (2055), and 2066 to 2094 (2080) as compared to the base period 1971 to 2000 (1985). Hydrologic variables were produced using Variable Infiltration Capacity as driven by downscaled climate model forcings. The selection of time periods is explained in appendix B5.

Figures B6-10 through B6-21 are spatial plots of the changes in these parameters for four seasons. The seasons are defined as: Fall (October, November, and December [OND]); Winter (January, February, and March [JFM]); Spring (April, May, and June [AMJ]); and Summer (July, August, and September [JAS]). Separate figures have been provided for the three future periods.

FIGURE B6-1
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
01 – Colorado River at Glenwood Springs, Colorado

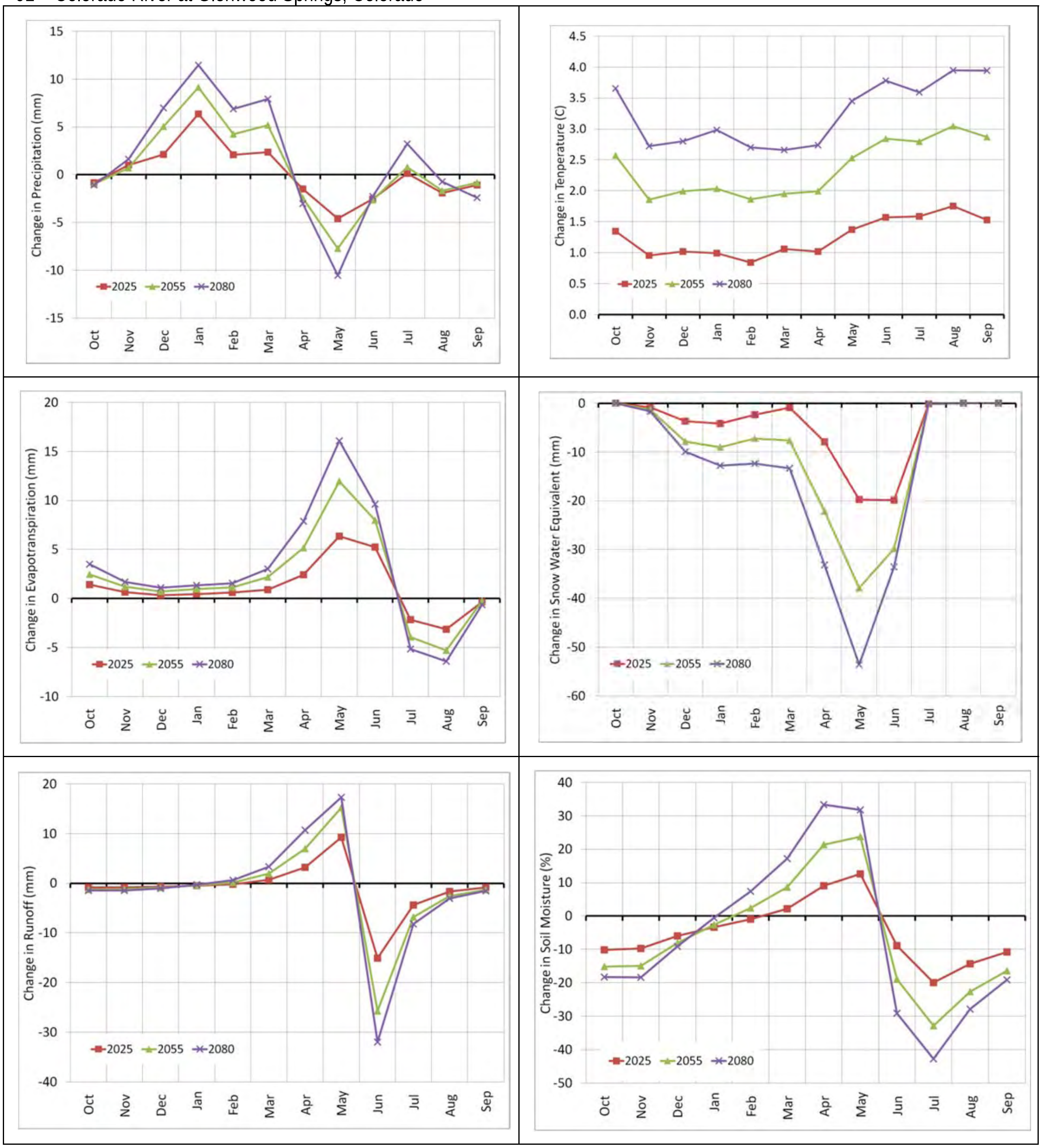


FIGURE B6-2
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
04 – Gunnison River at Blue Mesa Reservoir, Colorado

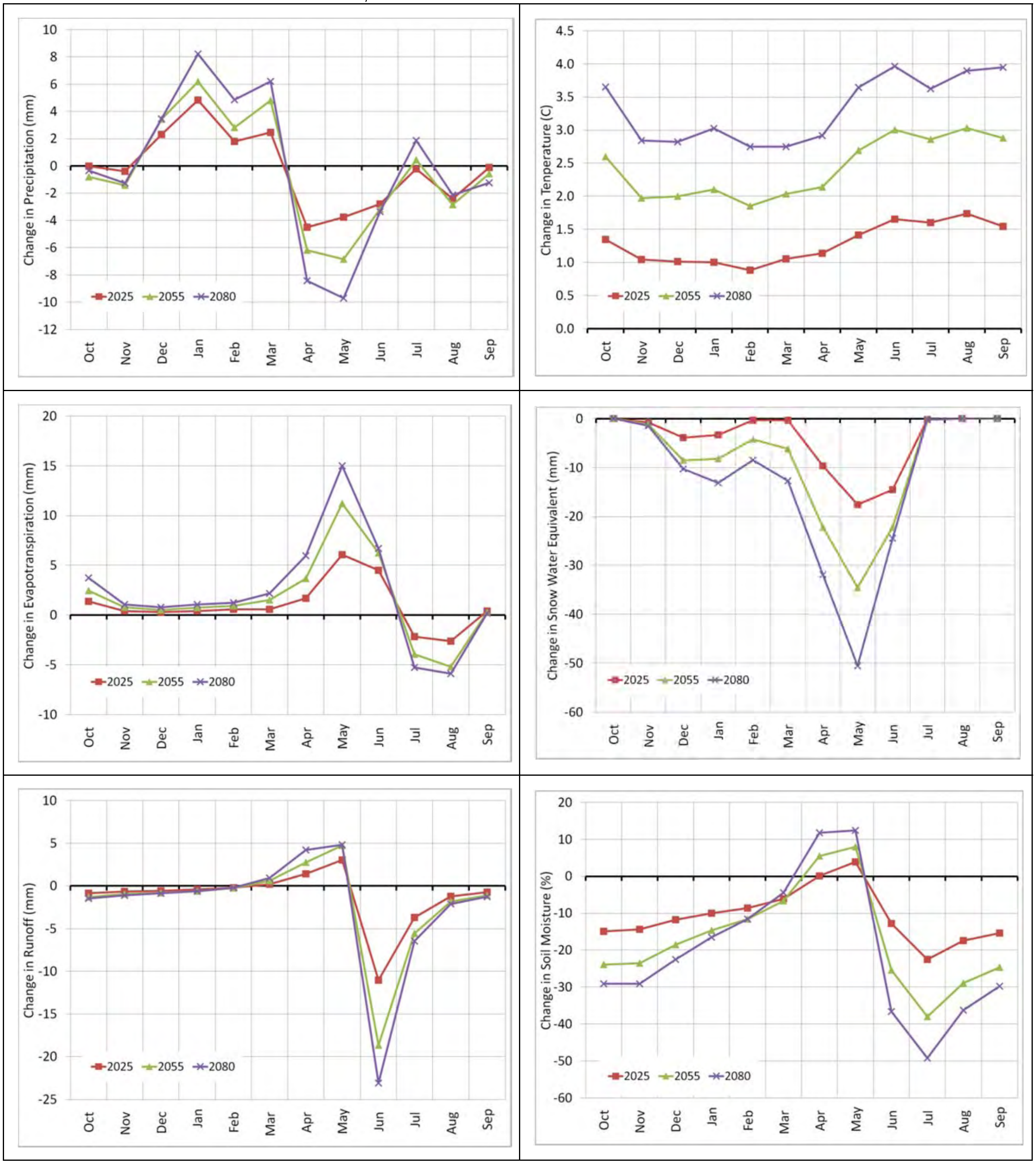


FIGURE B6-3
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
09 – Green River below Fontenelle Reservoir, Wyoming

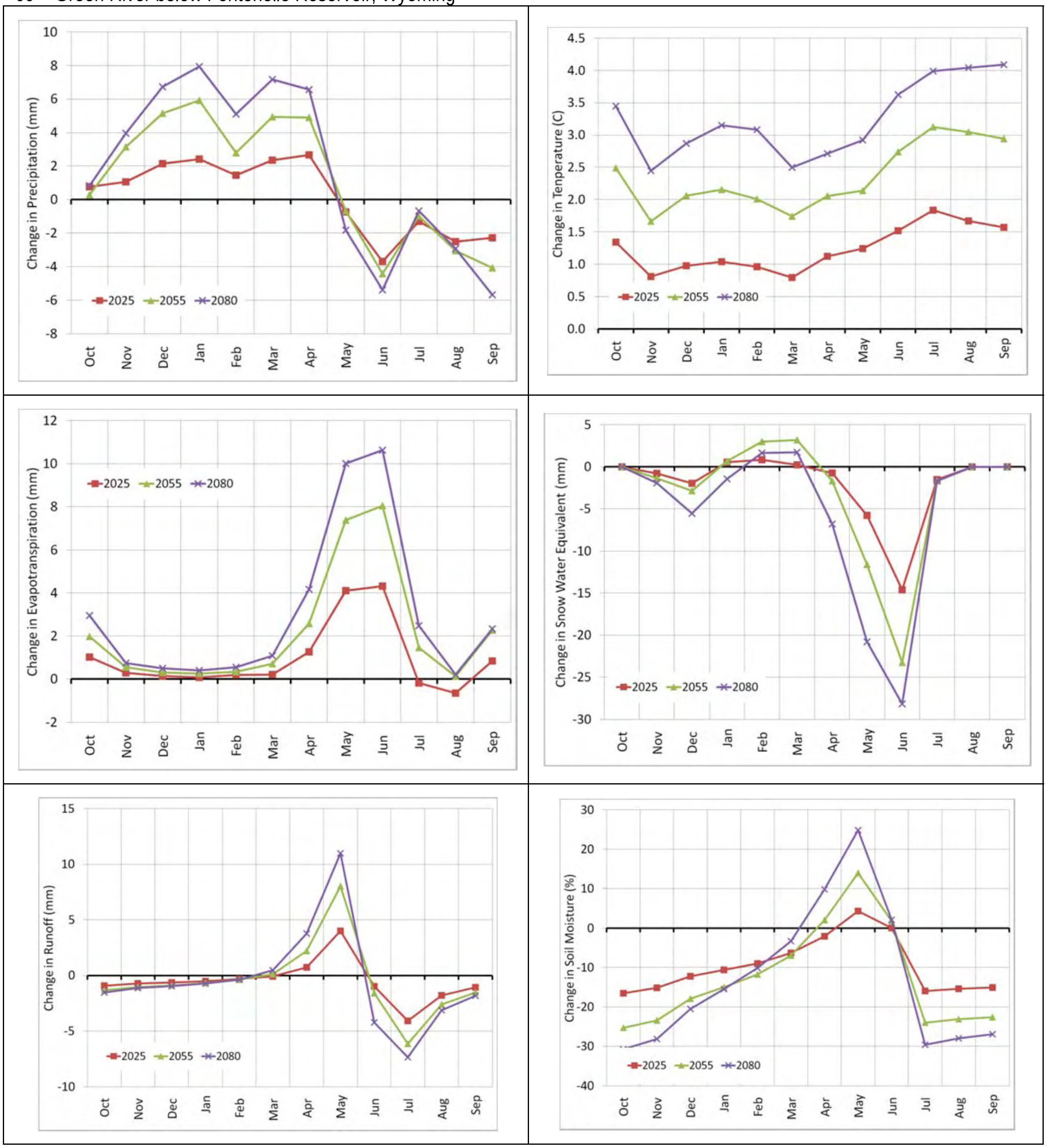


FIGURE B6-4
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
12 – Yampa River near Maybell, Colorado

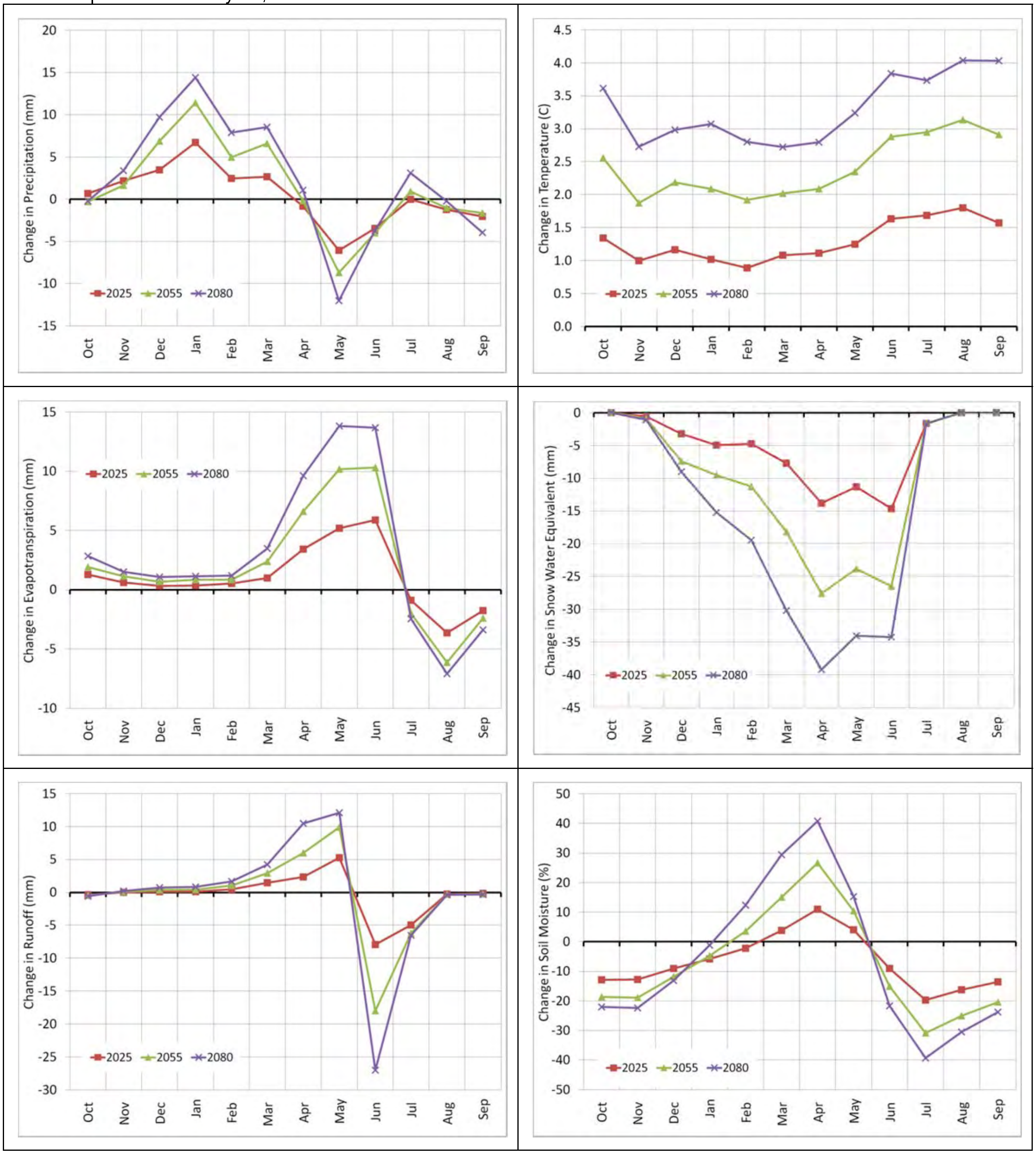


FIGURE B6-5
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
13 – Little Snake River near Lily, Colorado

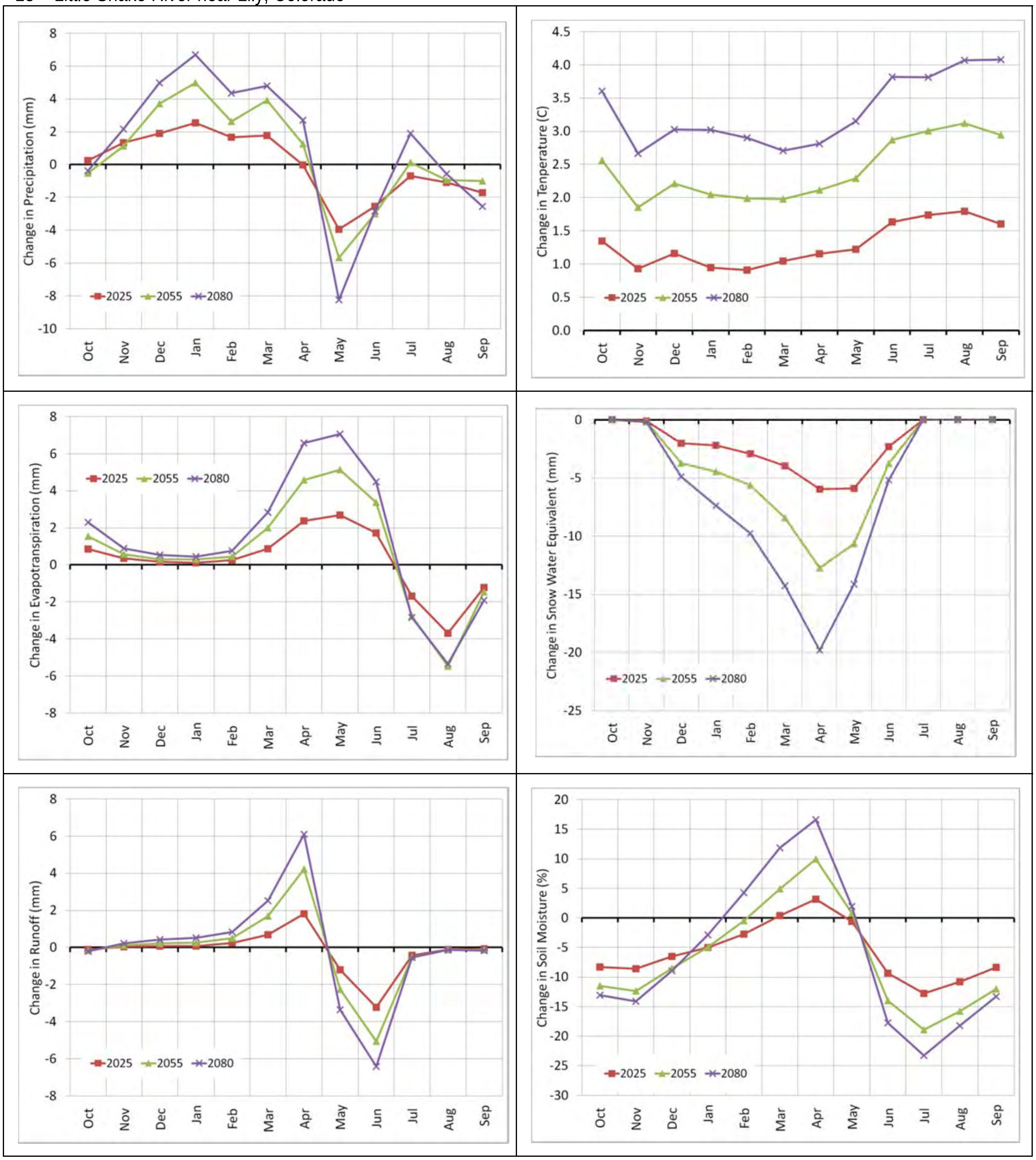


FIGURE B6-6
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
18 – San Juan River near Archuletta, New Mexico

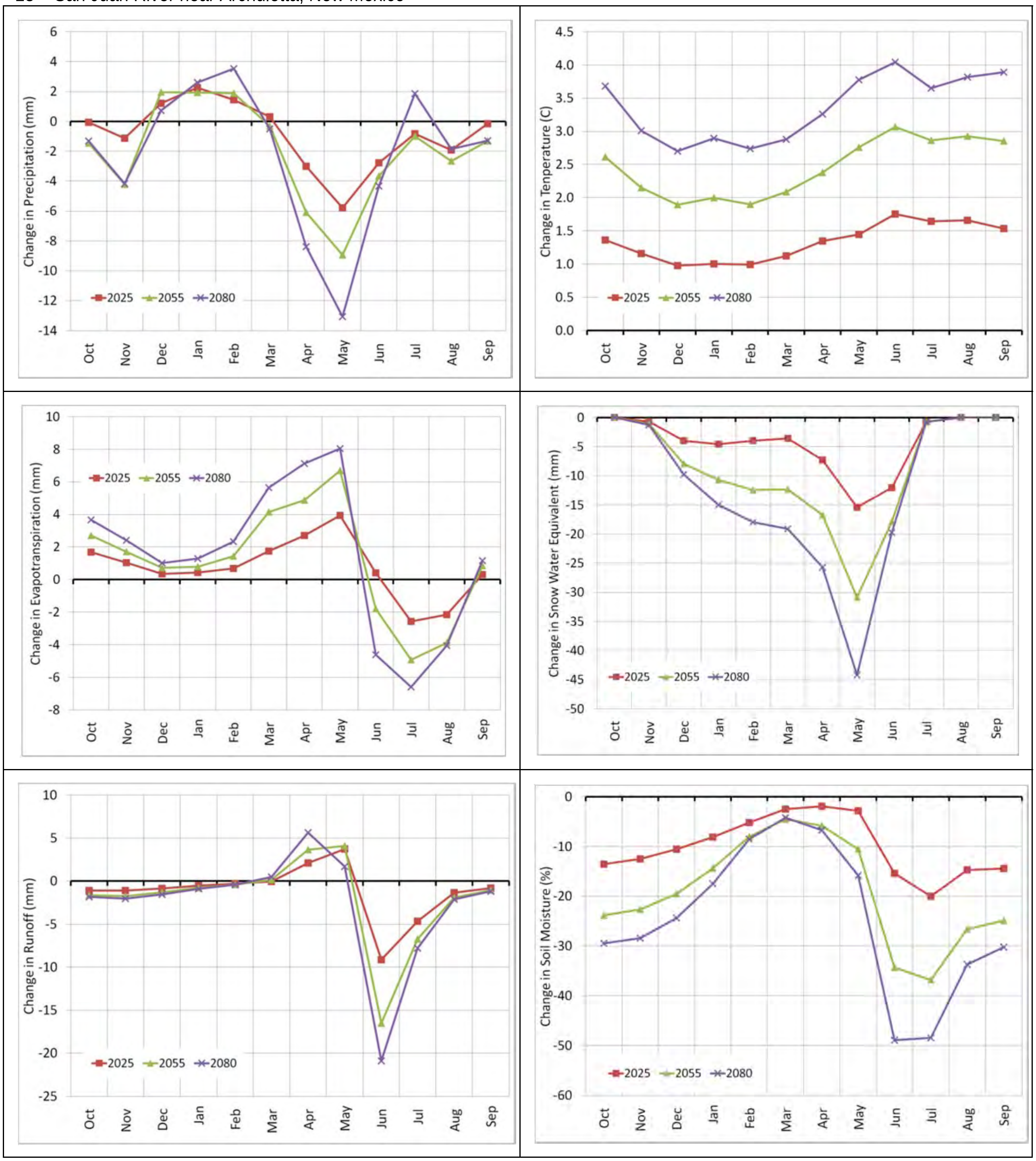


FIGURE B6-7
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
20 – Colorado River at Lees Ferry, Arizona

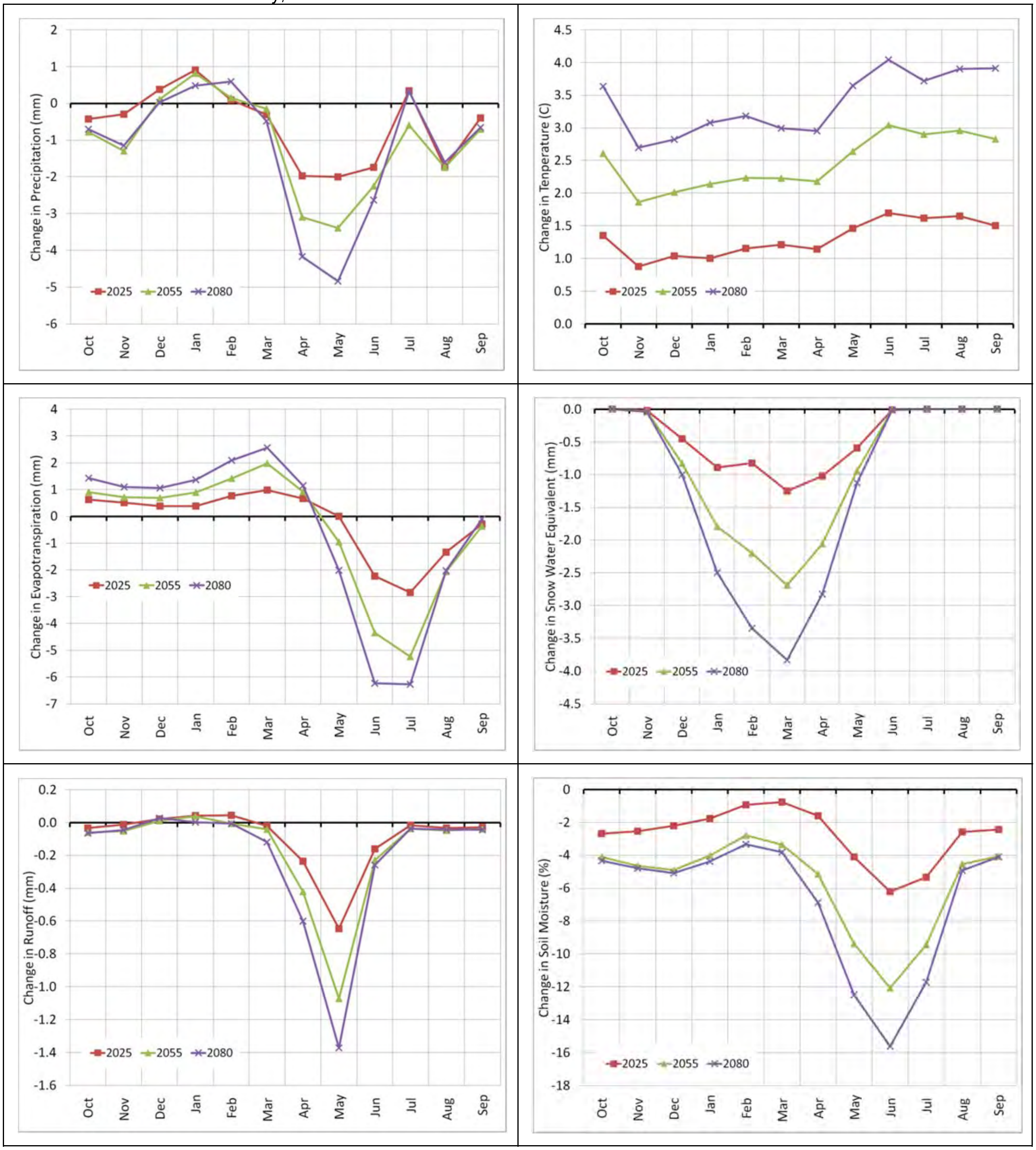


FIGURE B6-8
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
25 – Colorado River below Hoover Dam, Arizona-Nevada

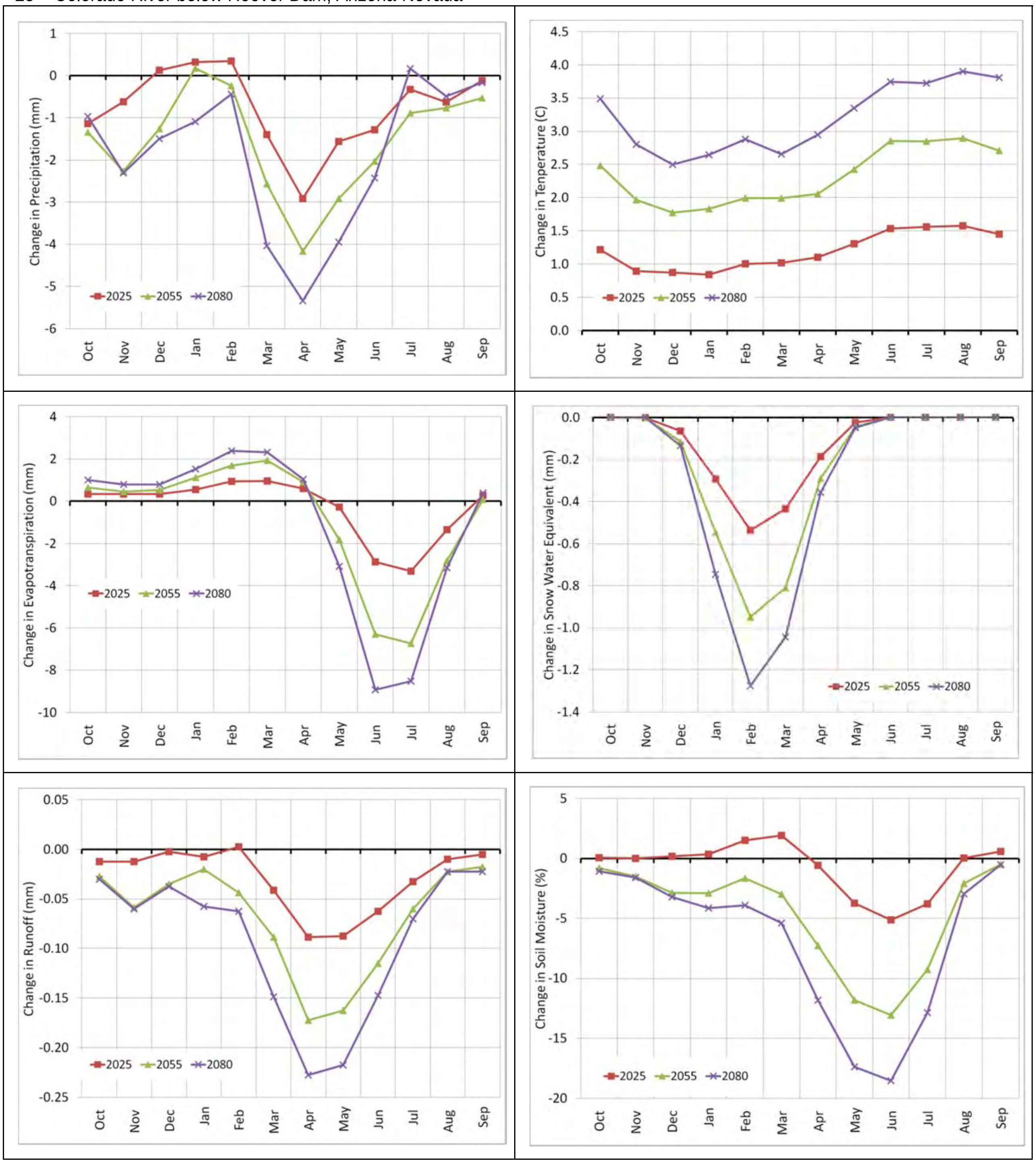


FIGURE B6-9
Projected Change in Mean Monthly Climatological and Hydrologic Parameters
29 – Colorado River Above Imperial Dam, Arizona

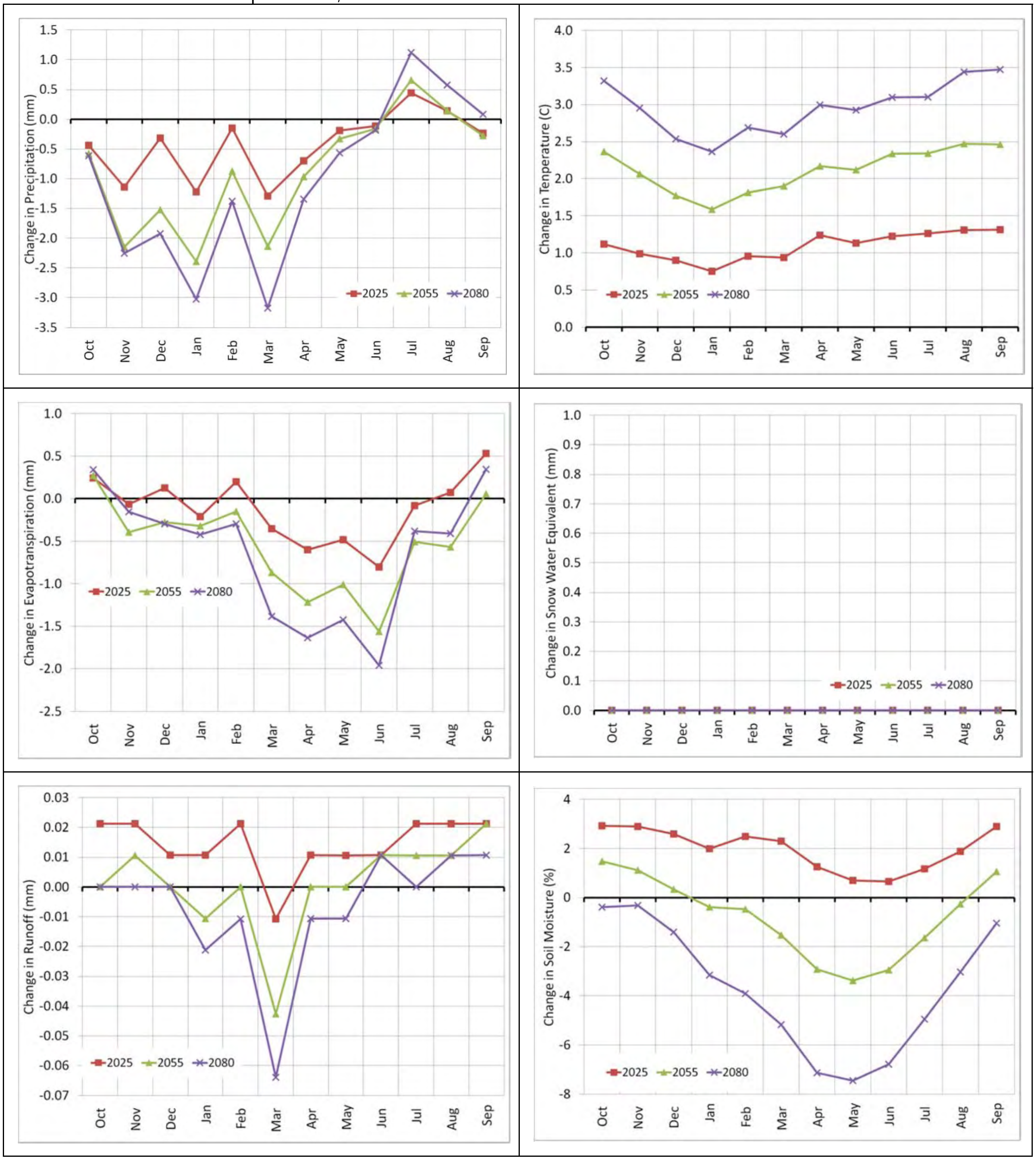


FIGURE B6-10
Projected Percent Change in Mean Seasonal Precipitation
2025 (2011–2040) versus 1985 (1971–2000).

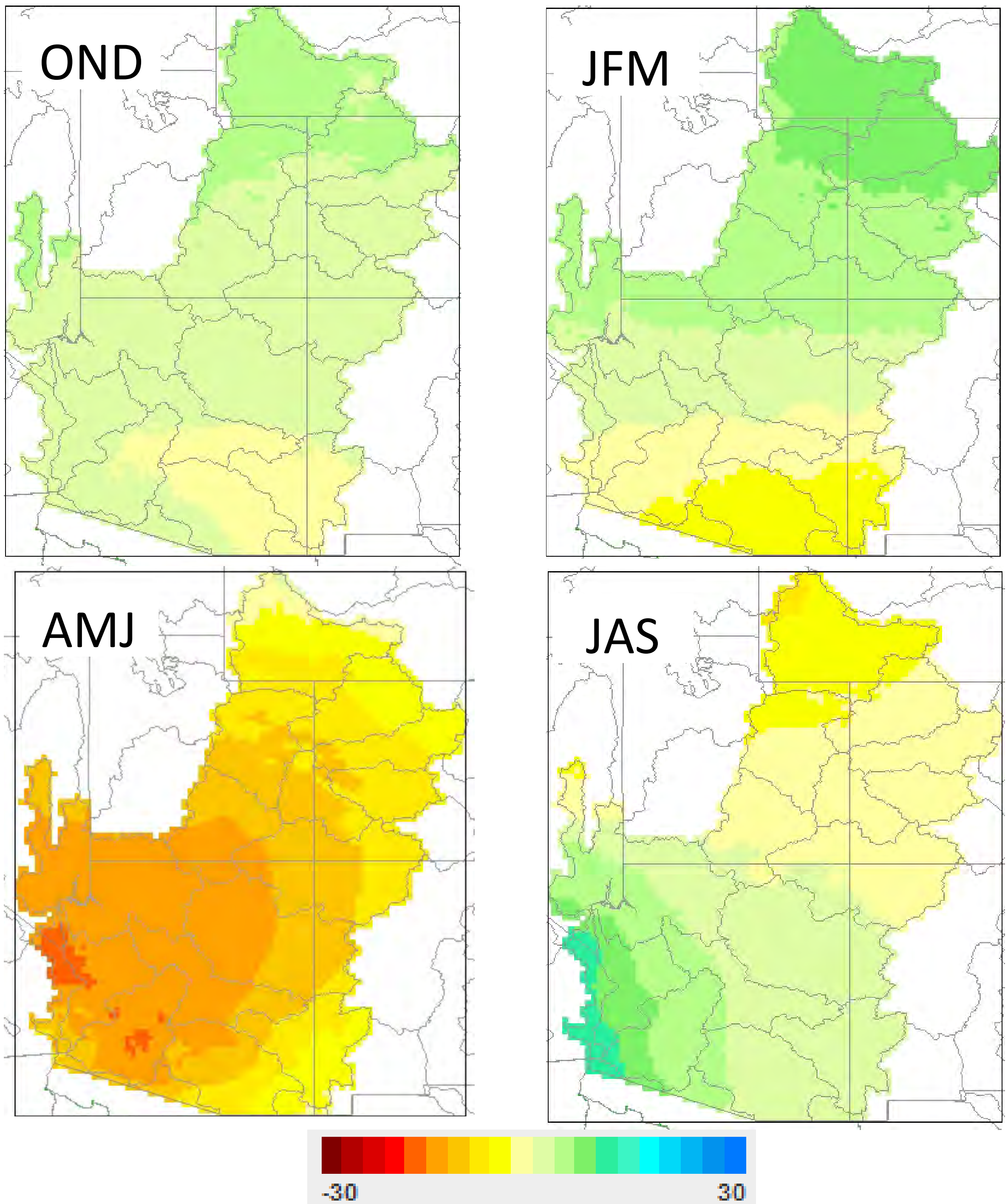


FIGURE B6-11
Projected Change in Mean Seasonal Air Temperature
2025 (2011–2040) versus 1985 (1971–2000). Change shown in degrees Celsius (°C).

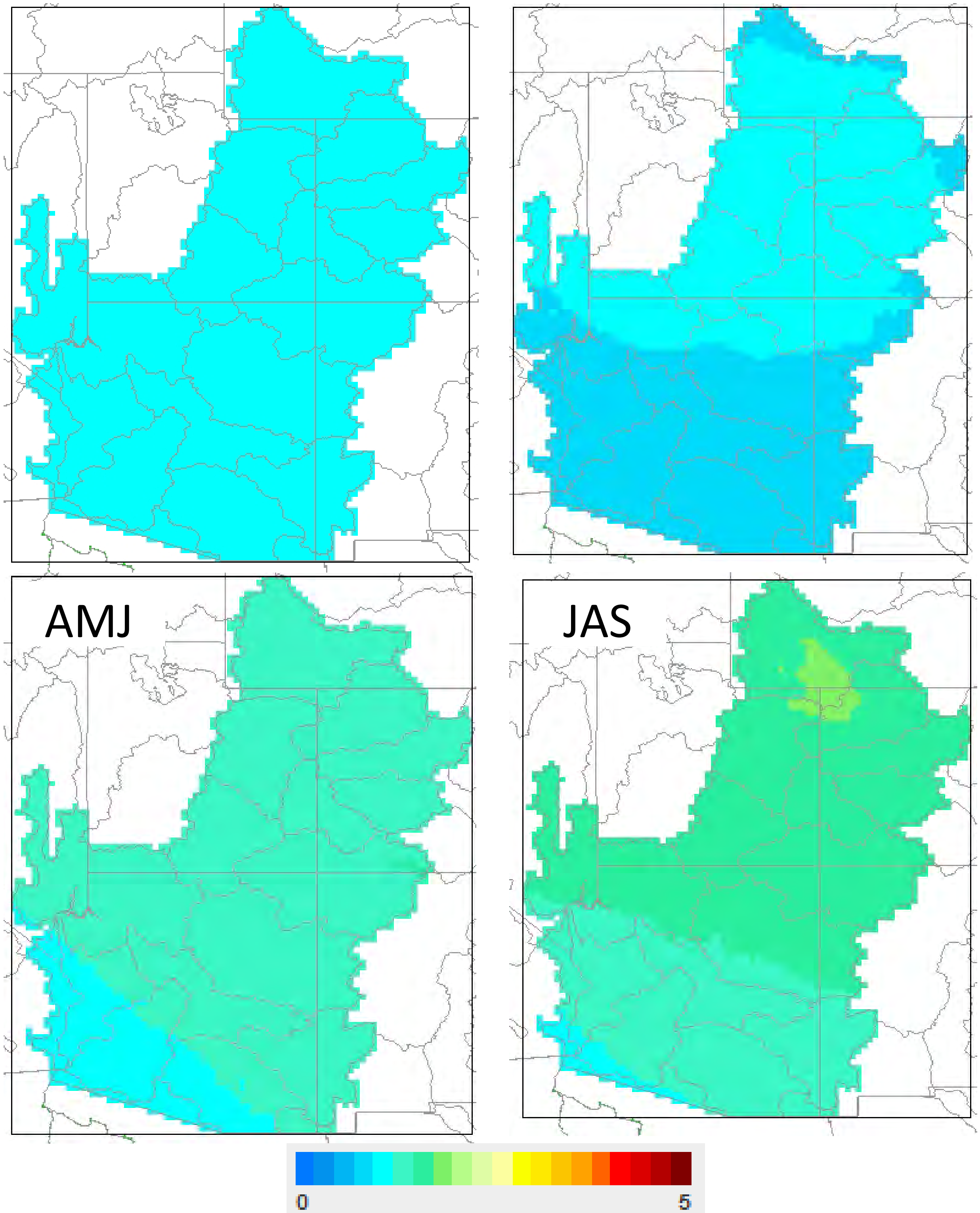


FIGURE B6-12
Projected Percent Change in Mean Seasonal Evapotranspiration
2025 (2011–2040) versus 1985 (1971–2000).

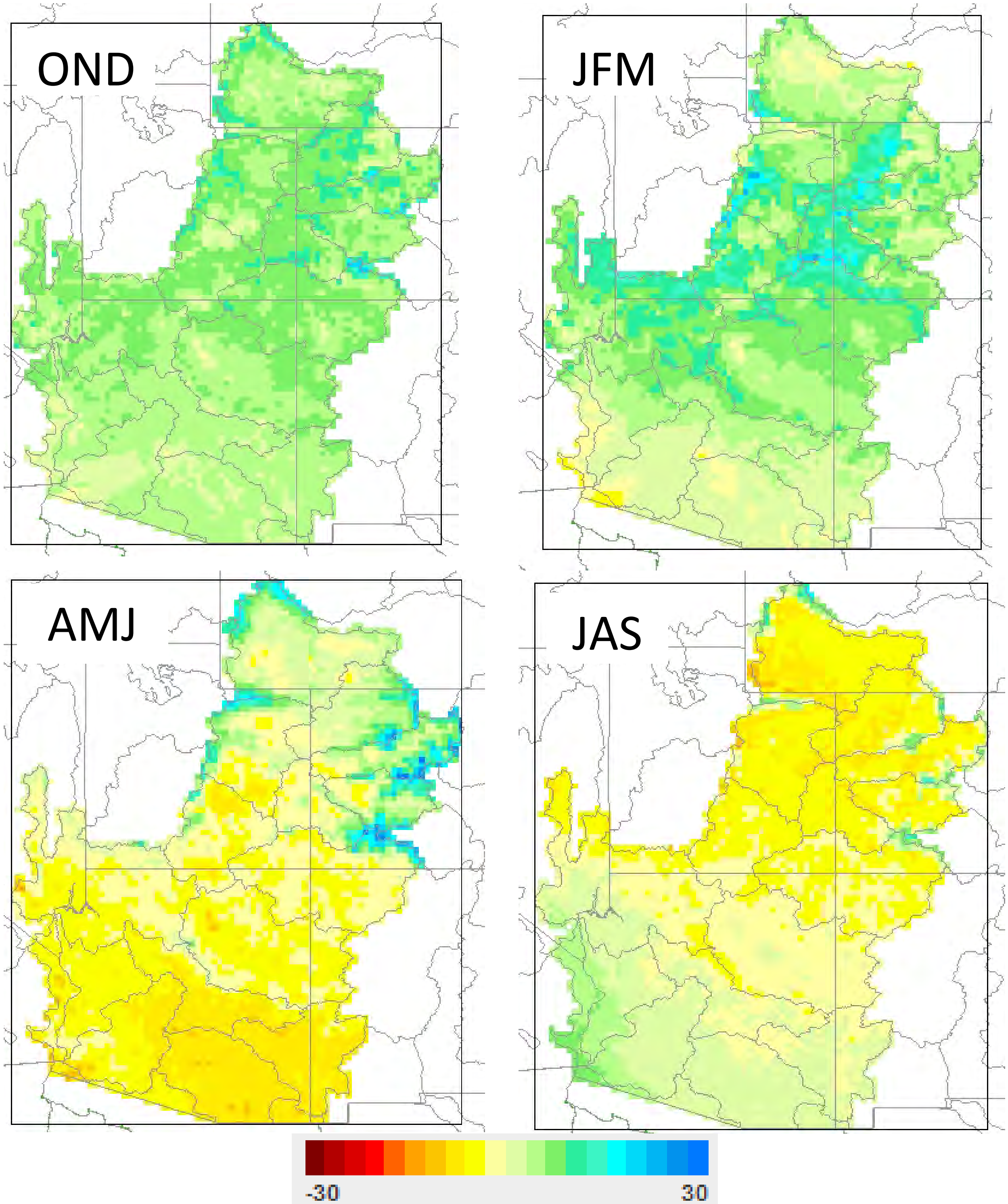


FIGURE B6-13
Projected Percent Change in Mean Seasonal Runoff
2025 (2011–2040) versus 1985 (1971–2000).

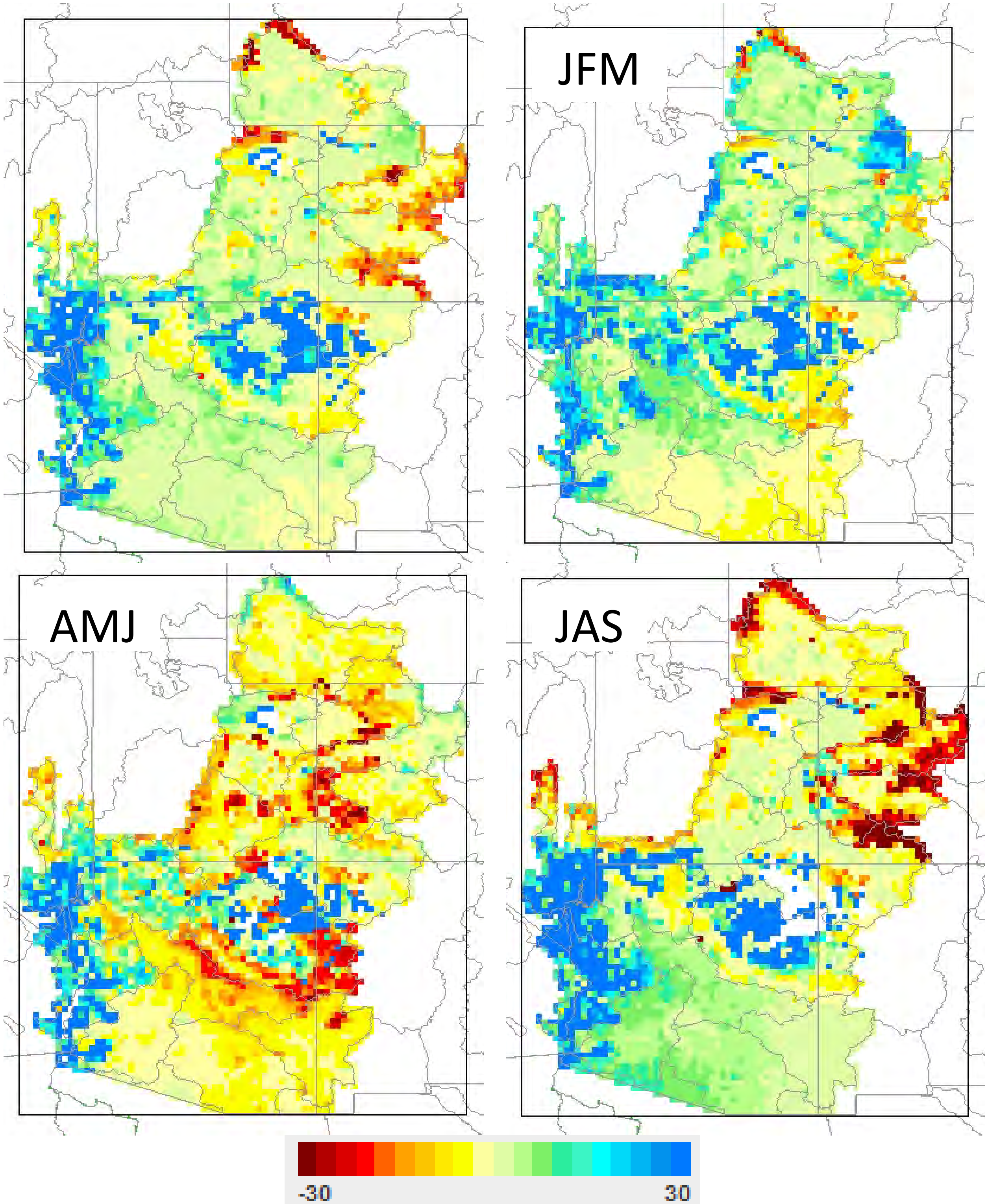


FIGURE B6-14
Projected Percent Change in Mean Seasonal Precipitation
2055 (2041–2070) versus 1985 (1971–2000).

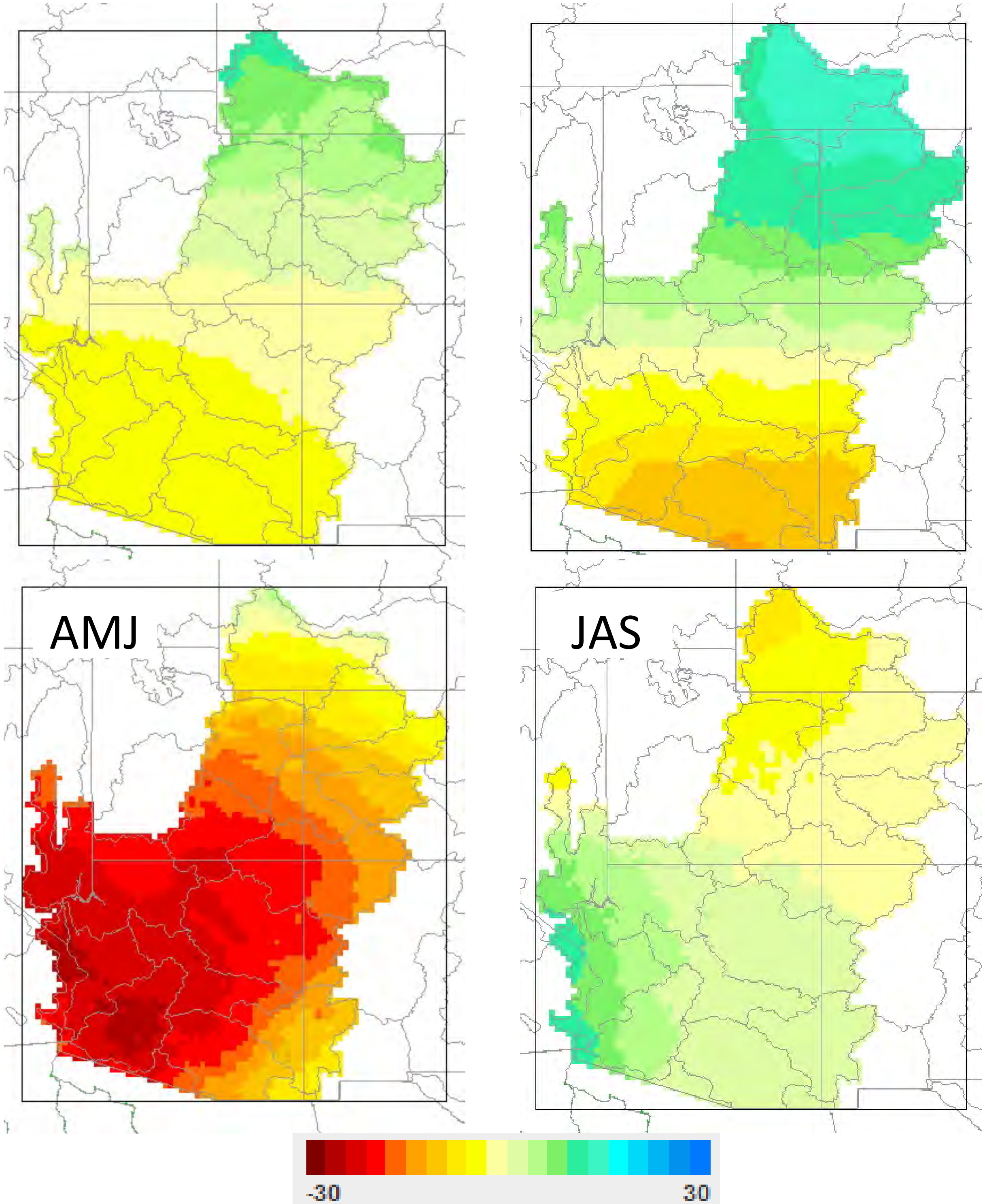


FIGURE B6-15
Projected Change in Mean Seasonal Air Temperature
2055 (2041–2070) versus 1985 (1971–2000). Change shown in degrees Celsius (°C).

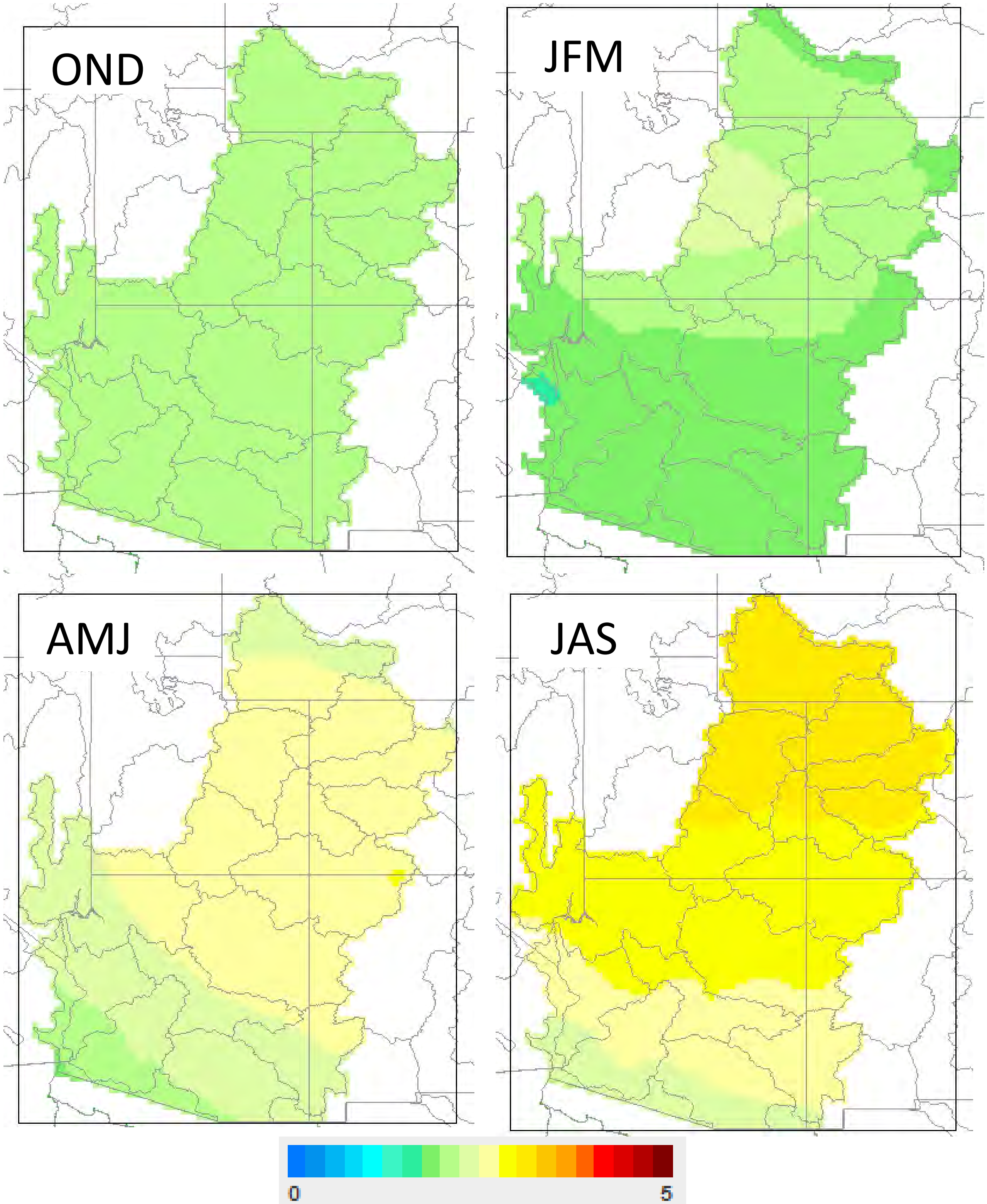


FIGURE B6-16
Projected Percent Change in Mean Seasonal Evapotranspiration
2055 (2041–2070) versus 1985 (1971–2000).

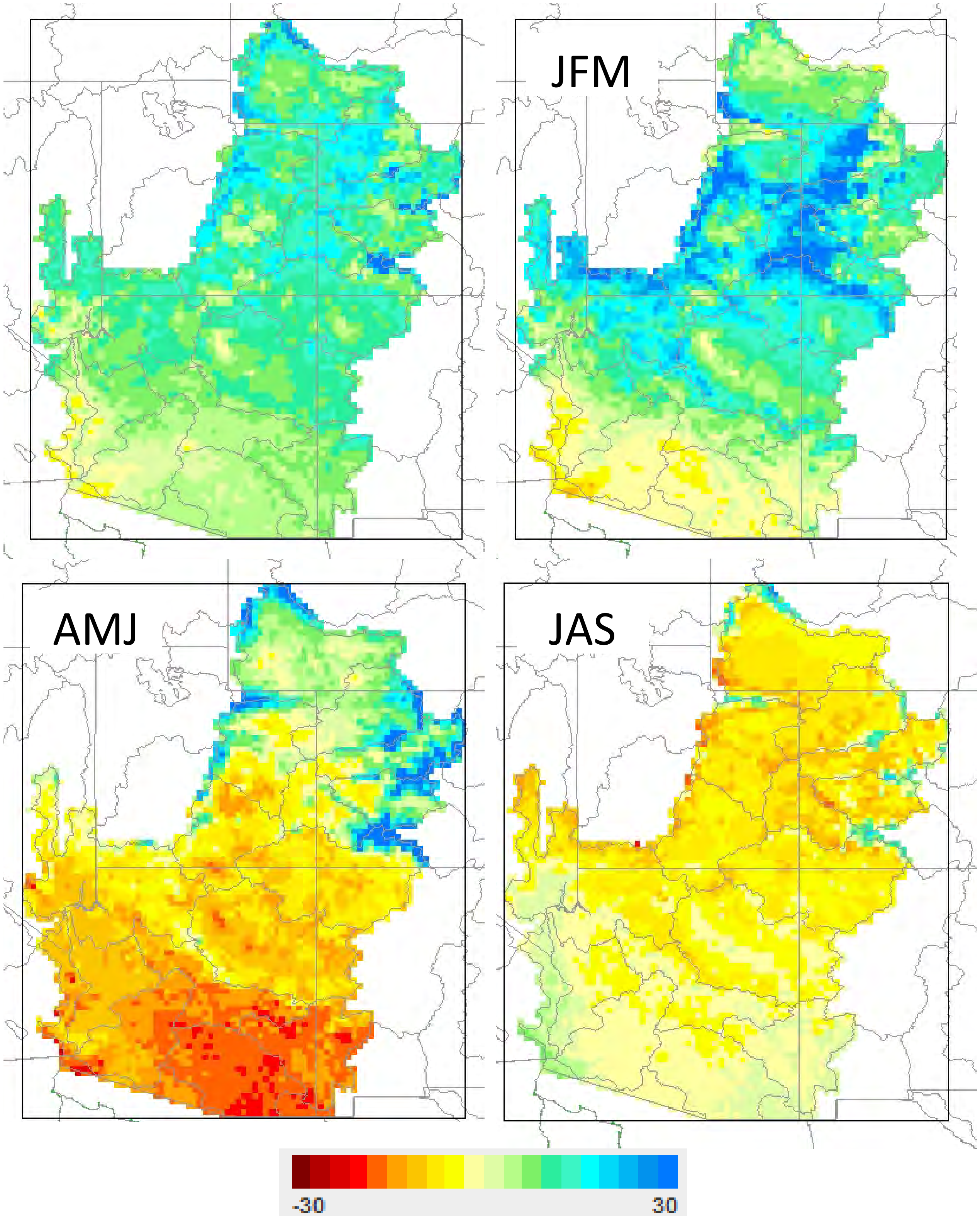


FIGURE B6-17
Projected Percent Change in Mean Seasonal Runoff
2055 (2041–2070) versus 1985 (1971–2000).

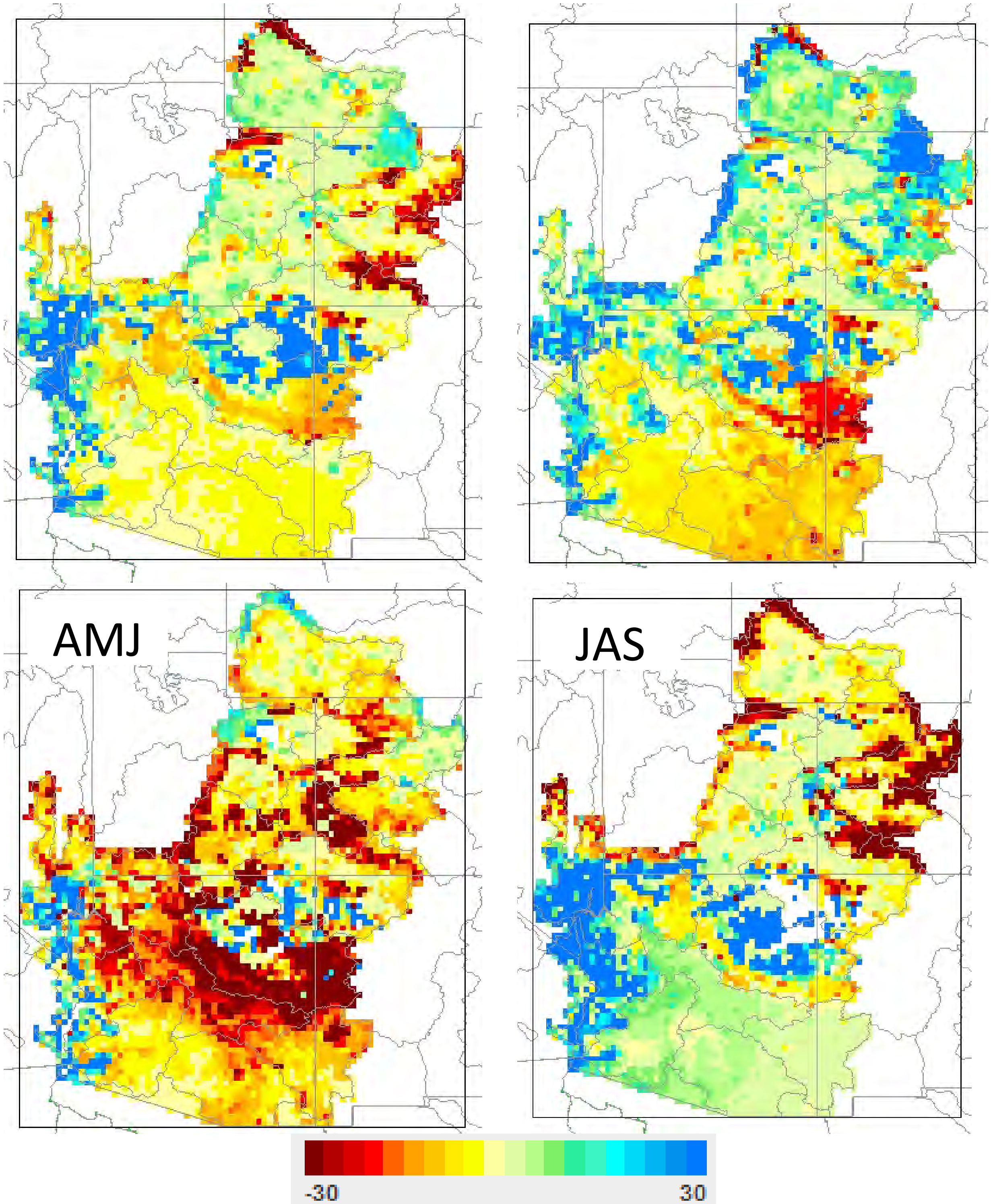


FIGURE B6-18
Projected Percent Change in Mean Seasonal Precipitation
2080 (2066–2095) versus 1985 (1971–2000).

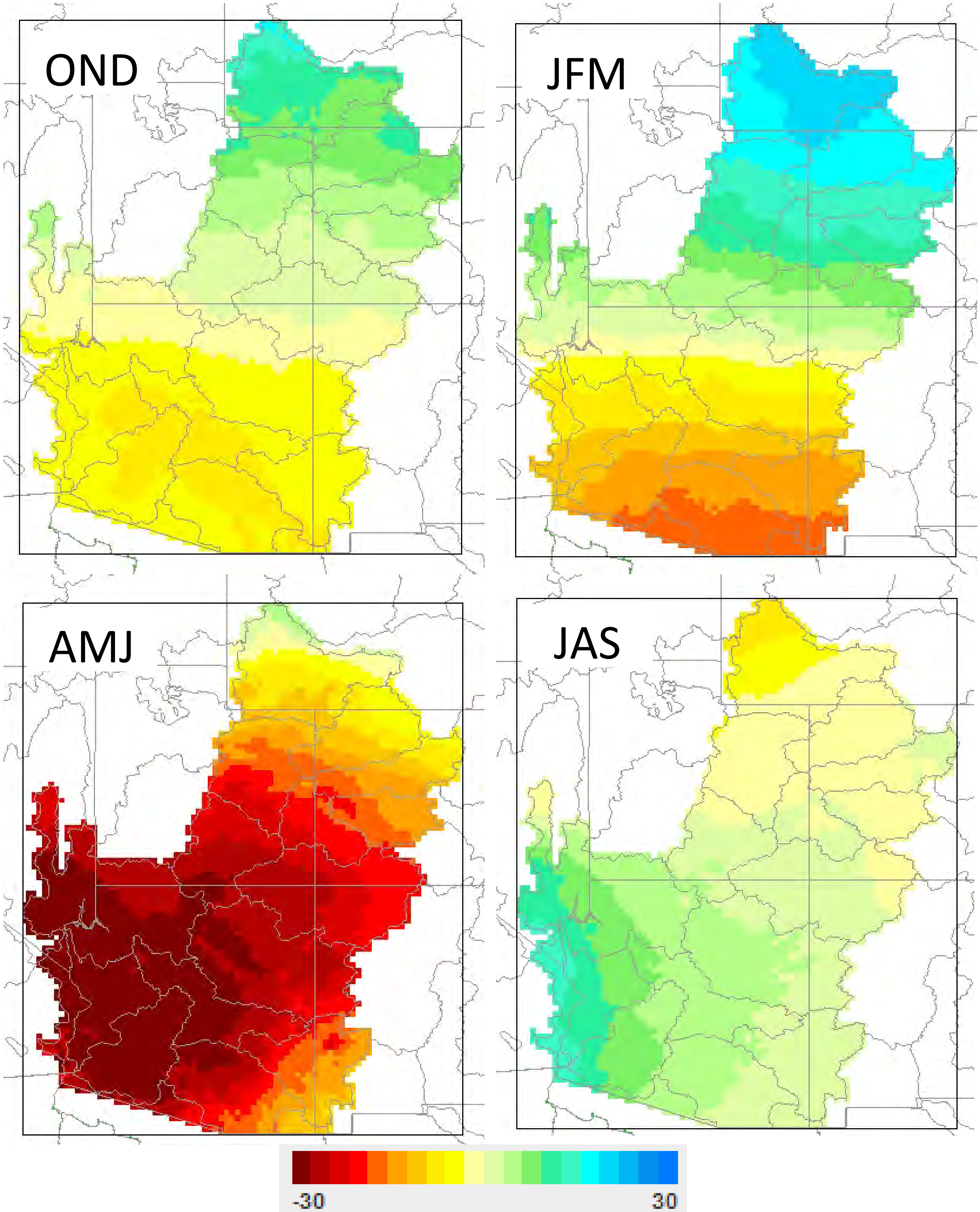


FIGURE B6-19
Projected Change in Mean Seasonal Air Temperature
2080 (2066–2095) versus 1985 (1971–2000). Change shown in degrees Celsius (°C).

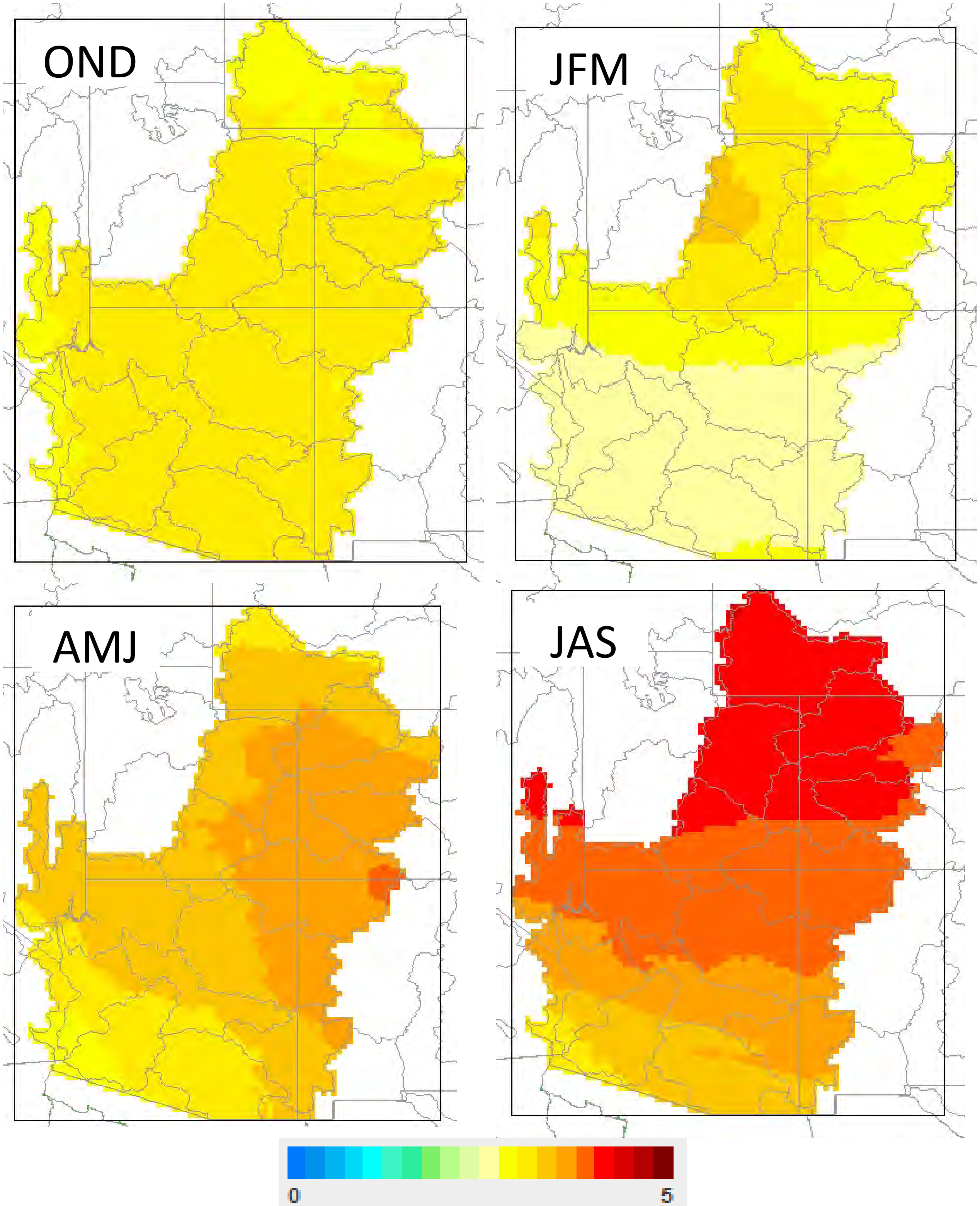


FIGURE B6-20
Projected Percent Change in Mean Seasonal Evapotranspiration
2080 (2066–2095) versus 1985 (1971–2000).

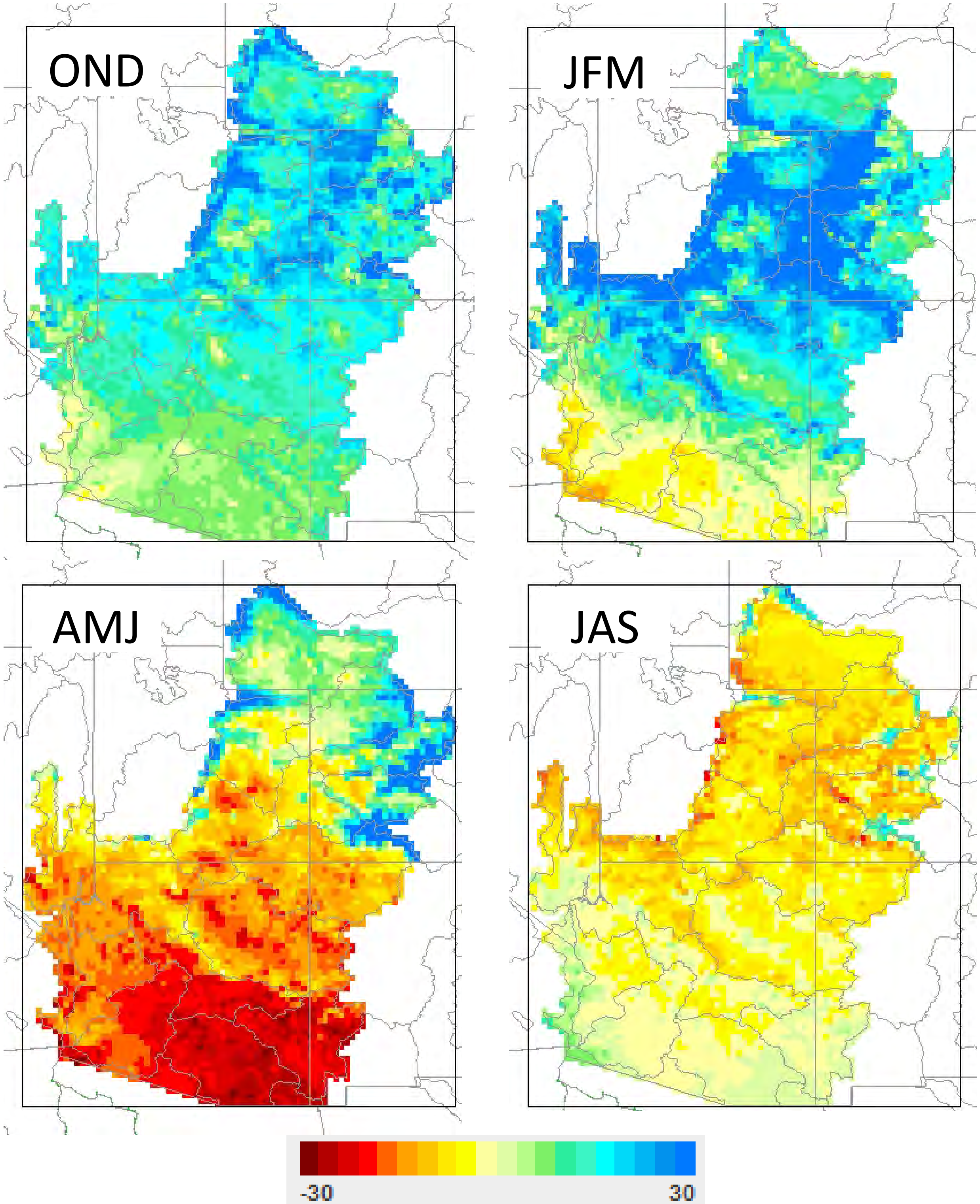
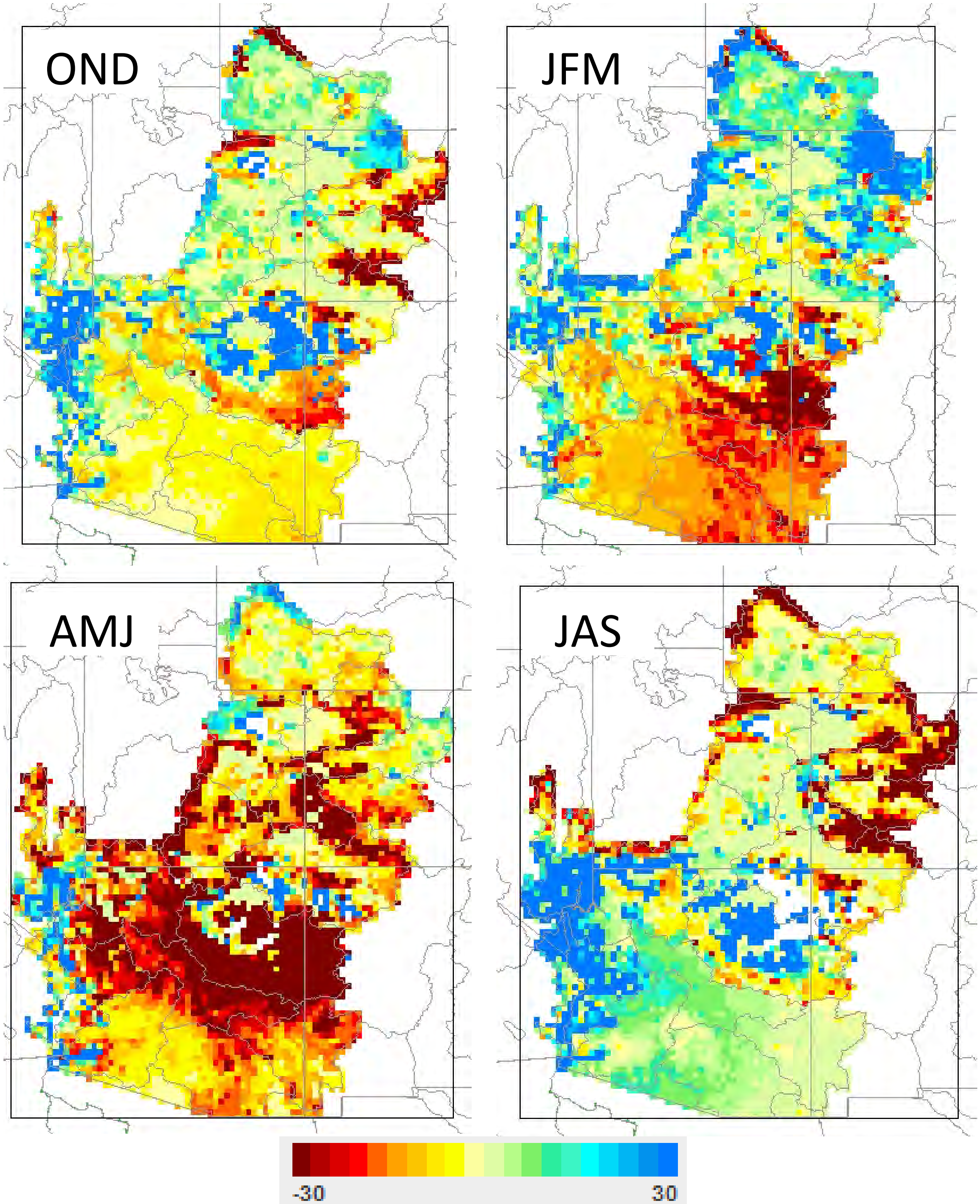


FIGURE B6-21
Projected Percent Change in Mean Seasonal Runoff
2080 (2066–2095) versus 1985 (1971–2000).



RECLAMATION
Managing Water in the West

Colorado River Basin Water Supply and Demand Study
Technical Report B — Water Supply Assessment

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

Technical Report B — Water Supply Assessment

U.S. Department of the Interior
Bureau of Reclamation

December 2012

Contents

Page

Tables

Figures

Appendices

Acronyms and Abbreviations

2007 Interim Guidelines Final EIS	*Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead Final Environmental Impact Statement*
°C	degrees Celsius
AMJ	April, May, and June
AMO	Atlantic Multi-decadal Oscillation
Basin	Colorado River Basin
Basin States	Colorado River Basin States
BCSD	bias correction and spatial downscaling
CDF	cumulative distribution function
CMIP3	Coupled Model Intercomparison Project Phase 3
CRSS	Colorado River Simulation System
EIS	Environmental Impact Statement
ENSO	El Nino Southern Oscillation
ET	evapotranspiration
GCM	General Circulation Model
GHG	greenhouse gas
in/d	inches per day
IPCC	Intergovernmental Panel on Climate Change
ISM	Indexed Sequential Method
JAS	July, August, and September
JFM	January, February, and March
kaf	thousand acre-feet
km	kilometer
maf	million acre-feet
Mexico	United Mexican States
mm	millimeters
mm/d	millimeters per day
netCDF	network common data format
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council

OND	October, November, and December
PET	potential ET
PDO	Pacific Decadal Oscillation
Reclamation	Bureau of Reclamation
RMSE	root mean square error
SNOTEL	snow-telemetry
SOI	Southern Oscillation Index
SRES	Special Report on Emissions Scenarios
Study	Colorado River Basin Water Supply and Demand Study
SWE	Snow water equivalent
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WCRP	World Climate Research Program
WWCRA	West-Wide Climate Risk Assessment

Technical Report B — Water Supply Assessment

1.0 Introduction

The Colorado River Basin Water Supply and Demand Study (Study), initiated in January 2010, was conducted by the Bureau of Reclamation's (Reclamation) Upper Colorado and Lower Colorado regions, and agencies representing the seven Colorado River Basin States (Basin States) in collaboration with stakeholders throughout the Colorado River Basin (Basin). The purpose of the Study is 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 contains four major phases to accomplish this goal: Water Supply Assessment, Water Demand Assessment, System Reliability Analysis, and Development and Evaluation of Options and Strategies for Balancing Supply and Demand.

Spanning parts of the seven states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming, the Colorado River is one of the most critical sources of water in the western United States. The Colorado River is also a vital resource to the United Mexican States (Mexico). It is widely known that the Colorado River, based on the inflows observed over the last century, is over-allocated and supply and demand imbalances are likely to occur in the future. Up to this point, this imbalance has been managed, and demands have largely been met as a result of the considerable amount of reservoir storage capacity in the system, the fact that the Upper Basin States are still developing into their apportionments, and efforts the Basin States have made to reduce their demand for Colorado River water.

Concerns regarding the reliability of the Colorado River system to meet future needs are even more apparent today. The Basin States include some of the fastest growing urban and industrial areas in the United States. At the same time, the effects of climate change and variability on the Basin water supply has been the focus of many scientific studies which project a decline in the future yield of the Colorado River. Increasing demand, coupled with decreasing supplies, will certainly exacerbate imbalances throughout the Basin.

It is against this backdrop that the Study was conducted to establish a common technical foundation from which important discussions can begin regarding possible strategies to reduce future supply and demand imbalances. The content of this report is a key component of that technical foundation and describes the Study's assessment of water supply. The purpose of the Water Supply Assessment is to determine the probable magnitude and variability of historical and future natural flows in the Basin. Natural flow represents the flow that would have occurred at a location, had depletions and reservoir regulation not been present upstream of that location.

Because the magnitude and variability of future water supply is uncertain, a set of future water supply scenarios were developed to explore that uncertainty, including the potential effects of future climate variability and climate change. The water supply projections were used to analyze future reliability of the river system to meet water demands, with and without future options and strategies. The Water Supply Assessment drew on the expertise of researchers and analysts worldwide who have been investigating the hydrology of the Basin and the dynamics of global climate change.

Initially published in June 2011 under Interim Report No. 1 with updates published in February 2012, this report replaces these earlier publications.

2.0 Approach to Water Supply Scenario Development

A scenario planning process was implemented to examine the uncertainty in future water supply and demand and is detailed in *Technical Report A – Scenario Development*. As noted in that report, a collaborative process that engages stakeholders was essential to the successful development of future scenarios. Numerous organizations participated in the Water Supply Assessment, including representatives of the Reclamation, Reclamation's Technical Service Center, the Basin States, U.S. Fish and Wildlife Service, National Oceanic and Atmospheric Administration (NOAA), federally recognized tribes, conservation organizations, and others interested in the Basin. This collaboration was accomplished through a variety of means, including participation in a Water Supply Sub-Team and direct contact with the organizations listed above. The Water Supply Sub-Team members and the points of contact are identified in appendix B1 of this report.

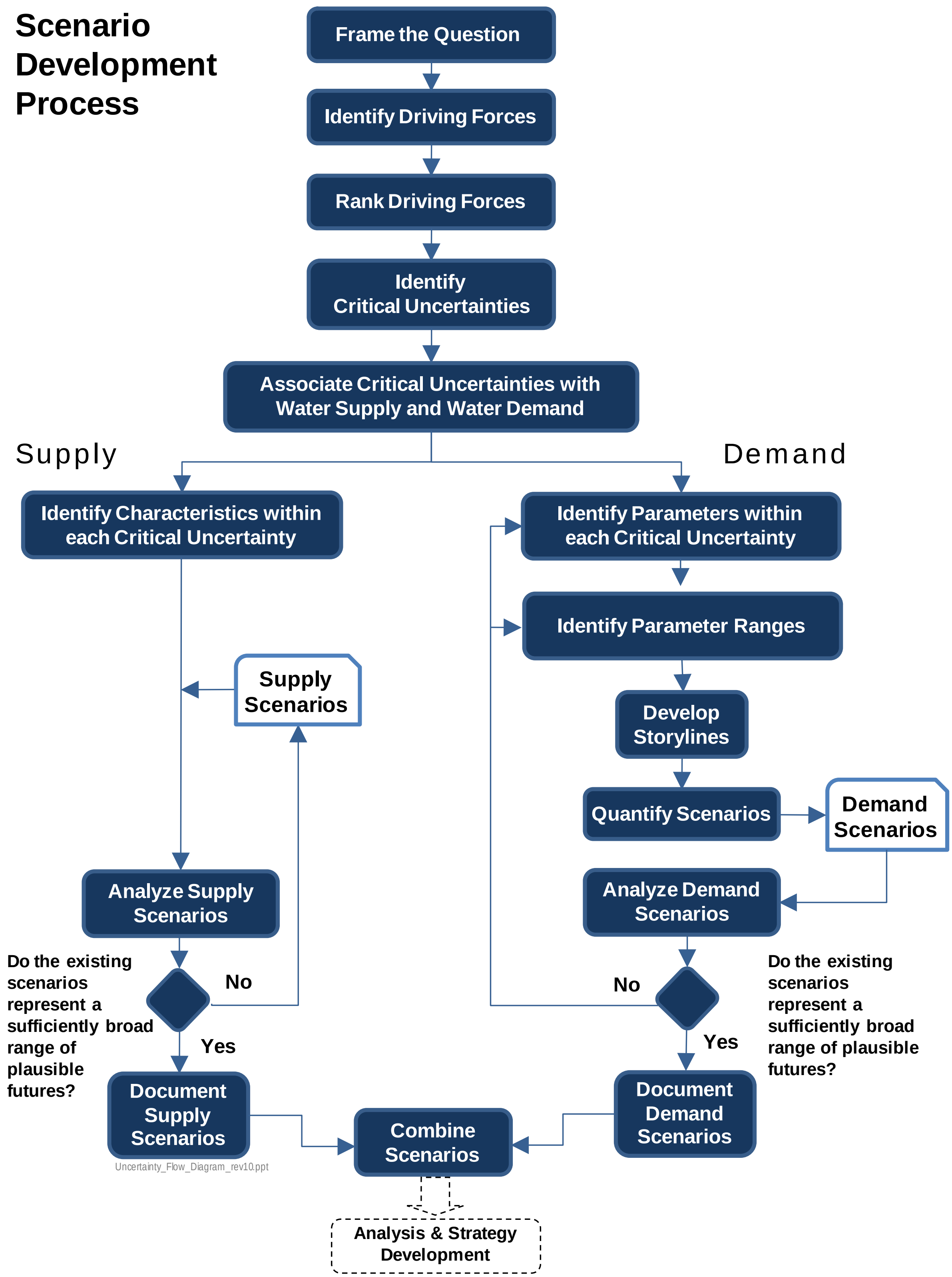
A scenario is an alternative view of how the future might unfold. Scenarios are not predictions or forecasts of the future. The scenario planning process involved identifying the key driving forces (i.e., the factors that will likely have the greatest influence on the future state of the system and thereby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

- Changes in Streamflow Variability and Trends
- Changes in Climate Variability and Trends

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

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

FIGURE B-1
Scenario Development Process



2.1 Identify Characteristics within each Critical Uncertainty

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

For purposes of the Study, it was determined that these previously used scenarios did not represent a sufficiently broad range of plausible futures because they did not include the consideration of changing climate beyond what has occurred in history. For this reason, a fourth scenario was developed that assumes the characteristics of the critical uncertainties Changes in Streamflow Variability and Trends, and Changes in Climate Variability and Trends are indicated by Downscaled General Circulation Model (GCM) projections and simulated hydrology.

2.2 Water Supply Scenarios

The following scenarios and associated themes were considered in the Study:

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

The scenarios each use well-established techniques to represent plausible future water supply conditions. The Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios use approaches previously developed to represent a range of hydroclimatic variability (annual to decadal scales) under a broad retrospective view. These scenarios are considered plausible in that they represent the range of hydroclimatic conditions experienced in the past. Future changes in climate variability and trends, and their influence on streamflow and Basin water supply, have been studied by several researchers in recent years. The Study represents the first time future climate scenarios have been included in Reclamation's Basin planning studies. For these reasons, greater detail is provided for the Downscaled GCM Projected scenario in this report. This scenario is considered plausible in that it reflects a growing body of scientific research suggesting future changes in hydroclimatic conditions globally and in the Basin. Each of the scenarios in the Study is considered a plausible future condition and is informative for future Basin planning.

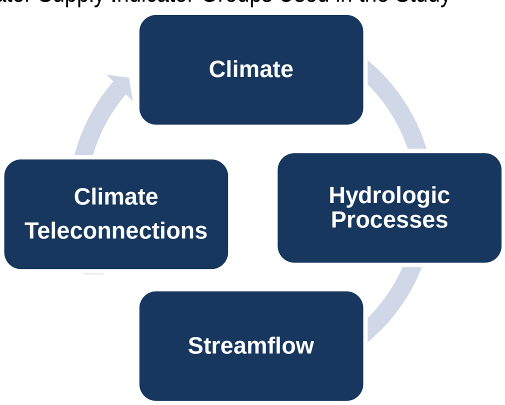
3.0 Summary of the Water Supply Assessment Approach

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

3.1 Tools and Methods

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

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



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

Climate indicators considered in this assessment were temperature and precipitation. Hydrologic process indicators were runoff, evapotranspiration (ET), snowpack accumulation (snow water equivalent [SWE]), and soil moisture. Climate and hydrologic process indicators were primarily derived from gridded data sets (Maurer et al., 2002; Maurer et al., 2007; Reclamation, 2011a), and spatial averaging was performed for selected sub-basins associated with Reclamation's natural flow computation points. The sub-basin averaging of climate and hydrologic process information allowed assessment of broader regions of the Basin than the detailed grid cell calculations.

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

Natural flow represents the flow that would have occurred at the location had depletions and reservoir regulation not been present upstream of that location. Natural flow has been computed historically by Reclamation[1] and is currently available for 29 locations throughout the Basin: 20 locations in the Upper Basin upstream of and including the Lees Ferry gaging station in Arizona; and nine additional locations below Lees Ferry, including the Paria River and other inflow points in the Lower Basin. These locations are shown in figure B-3. At this time, Basin-wide, natural flow estimates extend from 1906 through 2008[2]. Although all gages were not in place back to 1906, the existing records were extended back to 1906 using methods described in Lee et al. (2006).

For some tributaries in the Lower Basin (specifically the Little Colorado River, Virgin River, and Bill Williams River), U.S. Geological Survey (USGS)-gaged flows at specific locations near the confluence of the tributary and the Colorado River mainstream were used in place of natural flows. This approach was also taken for the Paria River, which joins the Colorado River just downstream of Lees Ferry, Arizona. In addition, the Gila River is not included in the Colorado River Simulation System (CRSS) and is therefore not included as one of the 29 locations where natural flow is estimated throughout the Basin. See *Technical Report C – Water Demand Assessment, Appendix C11 – Modeling of Lower Basin Tributaries in the Colorado River Simulation System,* for further discussion.

CRSS is Reclamation's primary Basin-wide simulation model used for long-term planning studies and, in its current configuration, requires natural flow inputs at these 29 locations on a monthly time step over the Study's planning horizon. This report describes the specific methods used to quantify, and results of, the water supply scenarios considered in the Study.

Additional information related to water supply data and methods is provided in appendix B2.

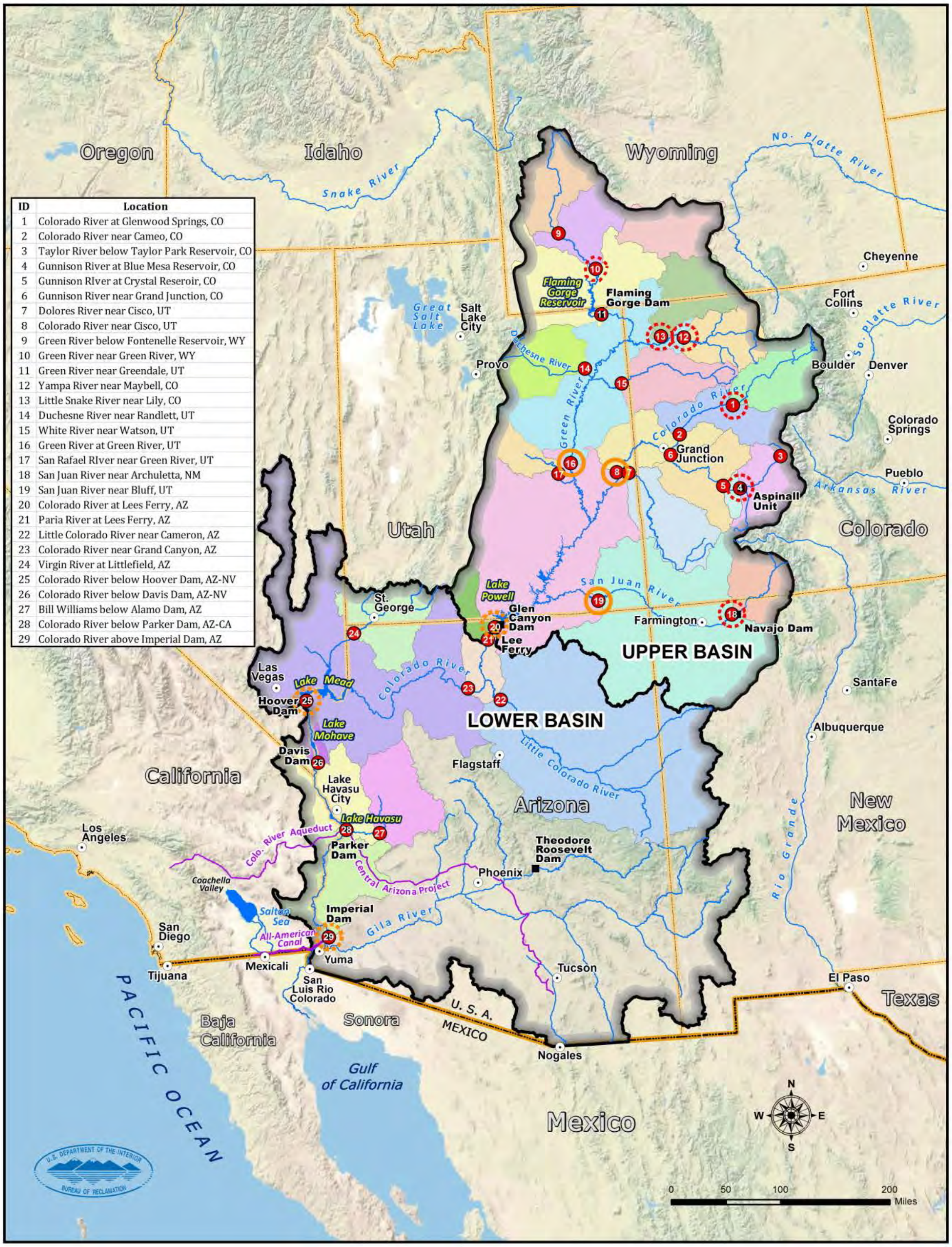
---

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

2 At the time the analysis for this report was performed, natural flow data were available only through 2008.

FIGURE B-3
Colorado River Basin and 29 Natural Flow Locations (Reclamation, 2011a)

Of the 29 streamflow locations, a subset was used for analysis in this report. Circled stations are used for describing climate and streamflow in this report; red dashed circled stations are used to describe climate, orange dashed circled stations are used to describe both climate and streamflow, and solid orange circled stations are used to describe only streamflows.



3.2 Sources of Data and Information

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

3.2.1 Literature Review

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

- The following studies: Gleick (1987); Nash and Gleick (1991, 1993); Hamlet and Lettenmaier (1999); McCabe and Wolock (1999a, 1999b); and Wilby et al. (1999) discuss climate change impacts on the hydrology and water resources of western U.S. river basins. All these studies assume or predict increasing temperatures, but disagree about both the magnitude and direction of precipitation changes.
- Nash and Gleick (1991) evaluate prescribed changes of +2 degrees Celsius (°C) and +4 °C, coupled with precipitation reductions of 10 and 20 percent. The 2 °C increase per 10 percent precipitation decrease resulted in a 20 percent streamflow reduction, while the 4 °C increase per 20 percent precipitation decrease resulted in a 30 percent runoff decrease.
- Christensen et al. (2004) project average temperature increases of 1.0 °C, 1.7 °C, and 2.4 °C, and precipitation decreases of 3, 6, and 3 percent for the Basin for the periods 2010 to 2039, 2040 to 2069, and 2070 to 2099, respectively, relative to the period 1950 to 1999 means. The temperature and precipitation changes lead to reductions of April 1 SWE of 24, 29, and 30 percent, and runoff reductions of 14, 18, and 17 percent for the three periods.
- Updated analyses by Christensen and Lettenmaier (2007) using a larger ensemble of climate projections, result in smaller mean projected reductions in Lees Ferry flows (less than 11 percent).
- Hoerling et al. (2009), in an attempt to reconcile streamflow estimates by several researchers, summarize the recent hydroclimatic analyses of the Basin and find that the projections range from a 5 to 20 percent reduction in streamflow by 2050.
- A recently released *Colorado River Water Availability Study* (Colorado Water Conservation Board, 2010) focuses on the State of Colorado’s hydrometeorological contribution to the

Colorado River system. The study describes the tools available to simulate river hydrology, agricultural demands, water allocation, and decision support.

- Several papers in a special issue of the *Proceedings of the National Academy of Sciences* on climate change and water in southwestern North America (Sabo et al., 2010) focus on the climate and water supply in the Basin. Cayan et al. (2010) provide an analysis of the current Colorado River drought and suggest that, although the current drought is exceptional in the observed record, future droughts in the Basin may be more severe and longer in duration. Woodhouse et al. (2010) provide the 1,200-year perspective on Southwestern drought, draw linkages of warming to paleo drought severity, and place the drought in context with the medieval period worst-case drought. Seager and Vecchi (2010) attribute the current and future Southwest drying to a broader expansion of the Hadley cell that causes storms to track farther north. It is important to note that the latter study (Seager and Vecchi, 2010) suggests decreases in winter (October through March) precipitation, although many other studies (including Cayan et al., 2010) suggest increases during this same period for much of the Basin. It is not clear whether this discrepancy is due to the large domain (southwest North America, from southern Mexico to the Oregon-California border and from the Pacific Ocean to the High Plains) that is being averaged, or due to the lack of regional/local spatial resolution of the GCM-based information.
- Das et al. (2011) further evaluate the effect of seasonal differences in warming on Colorado River streamflow changes. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report group of climate models indicates that climate warming over the Basin may be greater in summer than in winter. Das et al. (2011) find that annual Colorado River streamflow is more sensitive to warm season (April through September) warming than cold season warming (October through March), and is the most sensitive of the four western river basins evaluated. A 3 °C warming in the warm season results in a 13.3 percent reduction in annual flow, while the same warming applied during the cool season results in an annual flow reduction of only 3.5 percent. Climate warming, especially if amplified in summer as projected, may drive significant reductions in available supply, even if there is no reduction in precipitation.

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

3.2.2 Data Sources

The Water Supply Assessment relied on a variety of peer-reviewed datasets collected by Reclamation, other recognized federal sources, and hydrologic modeling results obtained from Reclamation’s West-Wide Climate Risk Assessment study (Reclamation, 2011c). The data sources and methods are described further in subsequent sections of this report and a complete listing is collectively included in appendices B2, B3, and B4.

4.0 Historical Supply

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

4.1 Methods

Historical daily temperature and precipitation data for 1950 to 2005 (Maurer et al., 2002[3]) were processed into average temperature and total precipitation for each month and year of the period. Monthly, seasonal, and annual statistics were computed for each grid cell (1/8th-degree resolution, or about 12 kilometers [km]) of the gridded meteorological dataset for the 1971 to 2000 historical period to represent the historical climatology and compare to future projected climates. The historical dataset was derived from individual NOAA Cooperative Observer station observations and gridded to the 1/8th-degree using mapping algorithms that account for station elevation, orographic effects, and other characteristics (Maurer et al., 2002).

Climate is defined by the World Meteorological Organization (2011) as the "average weather," or a statistical description in terms of the mean and variability of variables such as temperature, precipitation, and wind. Climate change is the shift in the long-term weather statistics, or trend, that a region experiences. Thus, climate change cannot be represented by single annual events or individual anomalies. That is, a single large flood event or particularly hot summer is not an indication of climate change, although a series of floods or warm years that statistically change the average precipitation or temperature over time may indicate climate change. The World Meteorological Organization recommends the use of a 30-year period for evaluating climate. At the time the Study was initiated, the established 30-year climatological period as described by NOAA (2011) was the 1971 to 2000 historical period. This period was used in the study to define the historical base climate. While NOAA has recently updated its climatological period to 1981 to 2010, climate and hydrologic information from various sources were not available at the time required to support this assessment for the Basin.

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

Historical hydrologic parameter data were generated by the Variable Infiltration Capacity (VIC) model for the period 1950 to 2005. The VIC model (Liang et al., 1994; Liang et al., 1996; Nijssen et al., 1997) is a spatially distributed macro-scale hydrologic model that solves the water balance at each model grid cell. The VIC model is populated with the historical temperature and

[3] Subsequent to Maurer et al. (2002), the climate dataset was extended to 2005 using identical methods.

precipitation data to simulate historical hydrologic parameters (Maurer et al., 2002). Appendix B4 provides details on the VIC model and its application in the Study. The simulated hydrologic parameters include ET, runoff (surface runoff), baseflow (subsurface runoff), soil moisture (in each of three soil layers), and SWE. Representative statistics describing these parameters were generated on monthly, seasonal, and annual bases. The statistical analysis was conducted on both grid cell and watershed bases. The results of the grid cell analysis produce the most informative map graphics and clearly show spatial variation at the greatest resolution possible, while the watershed basis provides an aggregate graphic of the variation across a natural flow station's watersheds.

Climate teleconnections were analyzed first by selecting indices that could have potential influence in streamflow changes for the Basin. Published research (such as Redmond and Koch, 1991; Diaz and Kiladis, 1992; and McCabe et al., 2004) indicates that the strongest correlations with Basin flows were observed with the ENSO and PDO indices. For ENSO, data were collected for both the ocean component (sea surface temperature anomalies) and the atmospheric component (sea level pressure anomalies). The sea surface temperature anomalies indicate the relative temperature state of the tropical Pacific Ocean as compared to normal (warm phase indicating El Nino conditions), while the sea level pressure anomalies are one measure of large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific. The two components are highly correlated and, combined, describe ENSO. The Southern Oscillation Index (SOI) was the primary dataset used in the Study to describe ENSO due to the longer period of data availability. The PDO indicates the longer-term (about 15 to 25 years) oscillation of the north Pacific Ocean sea surface temperatures. The PDO index, which indicates the warm or cool phase of the sea surface temperatures, has been linked to decadal-length period of above average or below average precipitation and was used directly in this assessment. The quantitative teleconnections analysis was based on the SOI and the PDO indices.

Only a qualitative discussion of the AMO is included in this report. For additional information pertaining to indices' choice, refer to appendix B2.

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

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

4.2 Results

4.2.1 Climate

The Basin contains climate zones ranging from alpine to desert and is fundamentally influenced by climate variability from seasonal to millennial scales (National Research Council [NRC], 2007). The Basin water supply, as is typical in many western river systems, strongly depends on snowmelt from high elevation portions (figure B-4) of the Upper Basin, with about 15 percent of the watershed area producing about 85 percent of the entire Basin's average annual runoff. Annual precipitation ranges from 84 millimeters (mm) (less than 4 inches) in southwestern Arizona to nearly 1,600 mm (63 inches) in the headwaters of Colorado, Utah, and Wyoming, as shown in figure B-5. Average temperatures vary considerably by season, Basin location, and elevation, as also shown in figure B-5. Warmest temperatures are seen in the southwestern Arizona summer and coolest in the headwaters during the winter.

The climate of the Basin exhibits important spatial and seasonal variability. To illustrate this variability, figure B-6 shows monthly average temperature and precipitation as watershed averages for the areas immediately upstream of the Colorado River near Glenwood Springs (Colorado), Colorado River at Lees Ferry (Arizona), and Colorado River above Imperial Dam (Arizona/California). These three locations reflect a coarse transect of the Basin from the headwaters to Imperial Dam.

As illustrated in figure B-6, the average temperature varies by more than 20 °C seasonally at each of the three locations and similarly across the Basin within seasons. Cool winter temperatures at the higher elevation portions of the Upper Basin cause much of the precipitation to fall in the form of snow. At lower elevations, warmer conditions exist and liquid precipitation is the dominant form. For most regions, the majority of the precipitation occurs in the cool season (fall and winter). Warmer temperatures in the spring and summer induce snowmelt at the higher elevations, and storms tend to be shorter and more intense. The summer precipitation does not contribute a significant portion of the Basin annual total. In the southwest portions of the Basin (Arizona, California, and Nevada), summer precipitation is locally important. The North American monsoon season plays a significant role in bringing moisture from the sub-tropical Pacific and Gulf of California and causes intense summer storms in the southwestern desert. The monsoon influence extends into Upper Basin states as well and can contribute to significant summer precipitation in New Mexico, Utah, and Colorado.

FIGURE B-4
Colorado River Basin Elevation (feet above mean sea level)
Derived from National Elevation Dataset, USGS, (HTTP://NED.USGS.GOV).

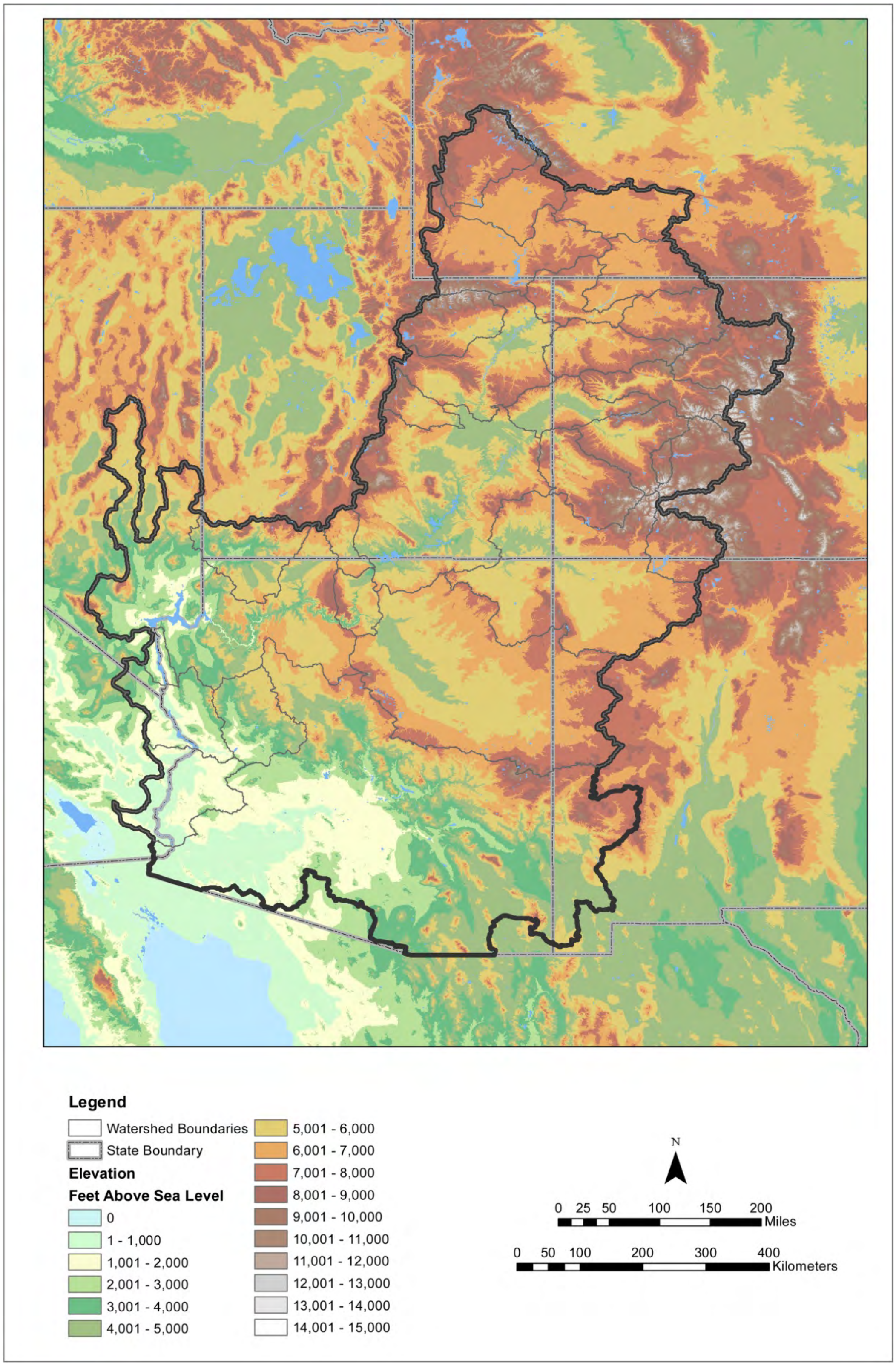


FIGURE B-5
Average Annual Temperature (°C) and Average Annual Precipitation (mm) for the Period 1971–2000
Derived from Maurer et al., 2002.

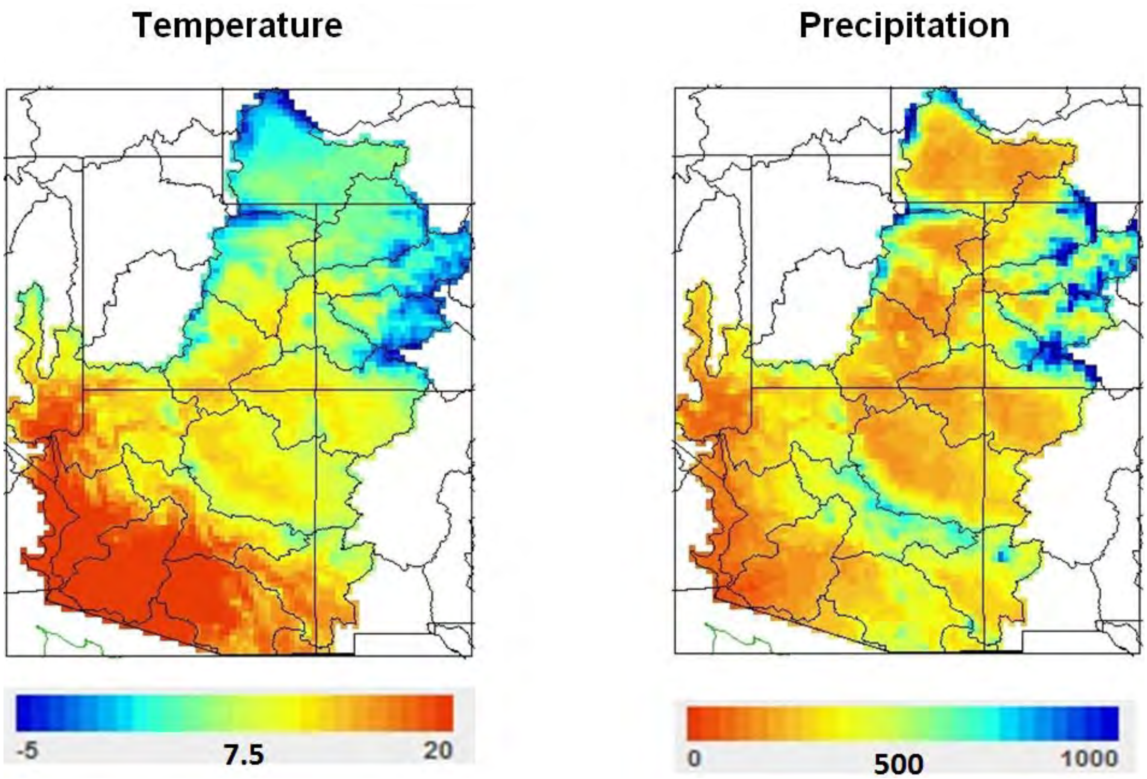
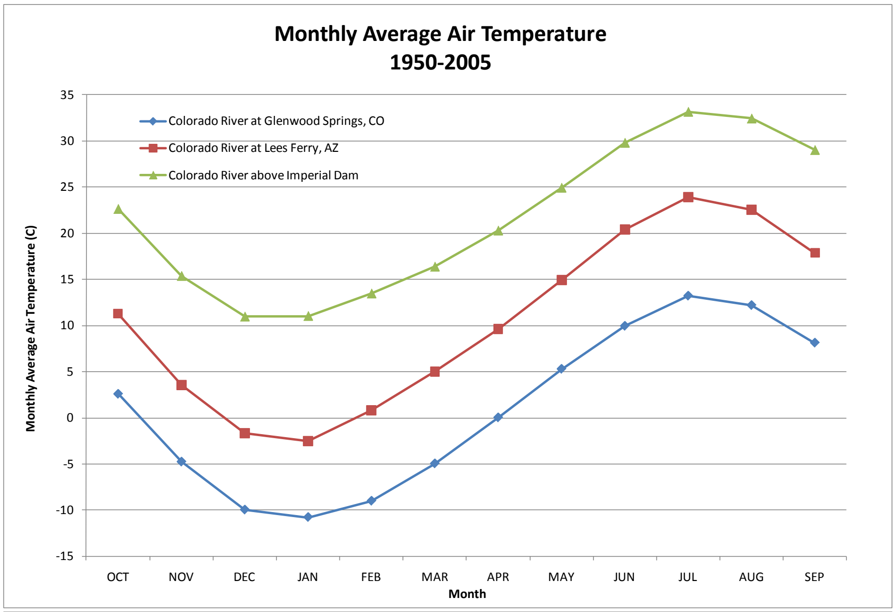
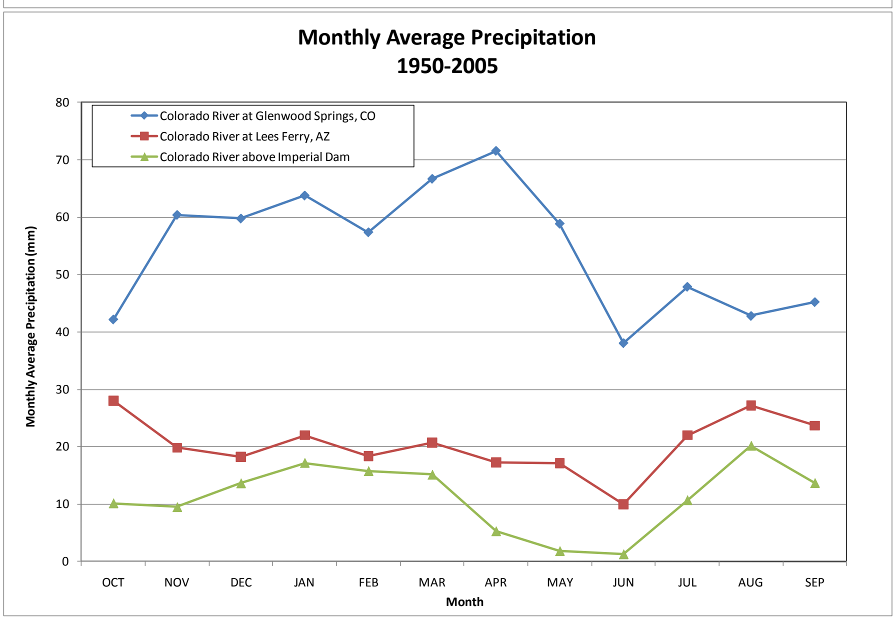


FIGURE B-6
Monthly Average Temperature and Precipitation for Three Representative Locations in the Colorado River Basin
Derived from daily gridded observed meteorology (Maurer et al., 2002) and averaged for the local watershed immediately upstream of the indicated point.



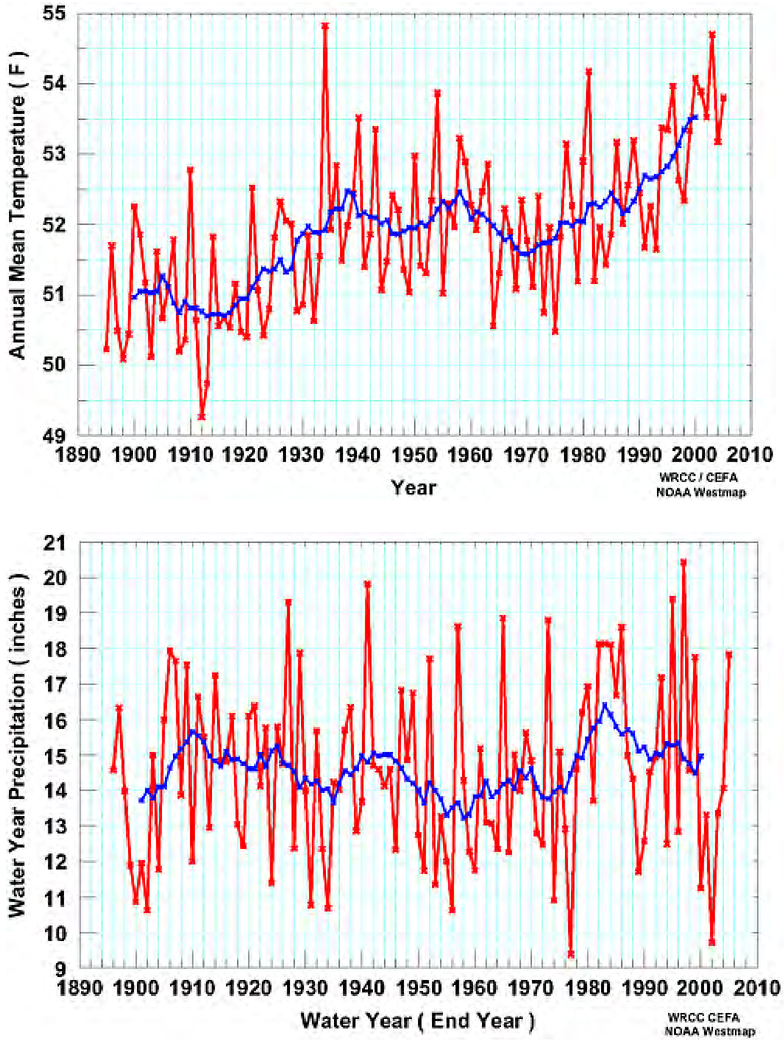


Trends in temperature and precipitation for the Basin have been studied by Groisman et al. (2001), McCabe et al. (2002), Piechota et al. (2004), Hamlet et al. (2005), Pagano and Garen (2005), Regonda et al. (2005), Andreasdis et al. (2006), Fassnacht (2006), Mote (2006), Christensen and Lettenmaier (2007), and several others. Long-term trends are summarized in the 2007 NRC summary report on hydroclimatic variability in the Basin (NRC, 2007). The long-term annual temperatures and precipitation amounts from the period 1895 to 2005 are shown in figure B-7. A significant increase in temperature is apparent in this figure, although periods of cooling have occurred historically. Most important is the warming trend that has occurred since the 1970s. This warming trend is also seen in the Upper and Lower Basins and with observed North American and global trends.

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

FIGURE B-7
Annual Average Surface Air Temperature for the Colorado River Basin, 1895–2005 (top); and Annual Water Year Average Precipitation for the Colorado River Basin above Lees Ferry, Arizona (bottom)

Red lines show annual values; blue lines show the 11-year running mean. Source: NRC (2007) and Western Regional Climate Center.



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

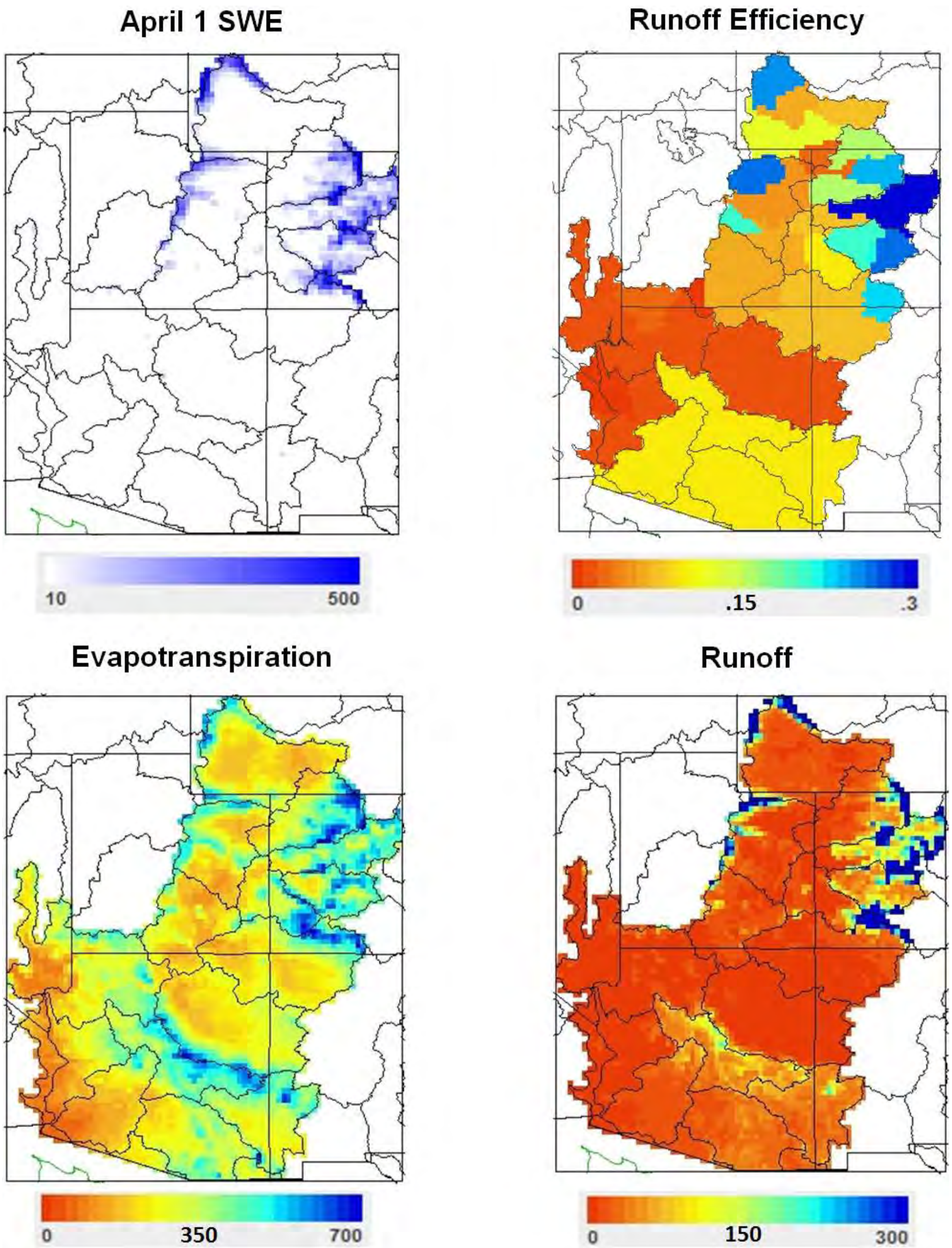
4.2.2 Hydrologic Processes

The hydrologic processes that describe the interaction between climate and the watershed landscape are critically important in determining water availability and the manner in which the Basin response may change under future climate. The regions of greatest precipitation in the Basin are those at high elevation in the headwaters of the Green, Colorado, and San Juan Rivers. Due to cold temperatures, these areas accumulate substantial snowpack that is critical to the Basin supply. Figure B-8 provides an estimate of the average spatially distributed April 1 SWE for the period 1971 to 2000 derived from a historical simulation of the VIC hydrology model. Important in this figure is the relatively small portion of the watershed that offers significant seasonal water storage in the form of snowpack. Although snow falls in other portions of the Basin, temperatures are generally not sufficiently cold to retain the snowpack for any great length of time. The remainder of this lower elevation portion of the watershed is primarily dominated by rainfall.

One way to synthesize many complex hydrologic processes at the watershed scale is to introduce the concept of runoff efficiency. Runoff efficiency is a measure of the effectiveness of a particular watershed in converting precipitation into runoff. Watersheds with very high runoff efficiencies dominate the overall contribution toward streamflow and have relatively lower losses. Watersheds with low runoff efficiencies have high losses and tend to be dominated by infiltration to soil moisture and consumptive use through ET. ET is the sum of evaporation from the land surface and plant transpiration. As can be seen in figure B-8, the watersheds with the highest efficiencies are the headwaters of the Colorado, Green, and San Juan Rivers. These watersheds are able to convert about 20 to 30 percent of the precipitation into runoff and baseflow; however, even in the headwater regions there is considerable variability in runoff efficiencies, with some values less than 10 percent. In the Lower Basin, average runoff efficiencies are all less than 10 percent and many watersheds have runoff efficiencies less than 5 percent. The runoff efficiency Basin-wide is about 12 percent.

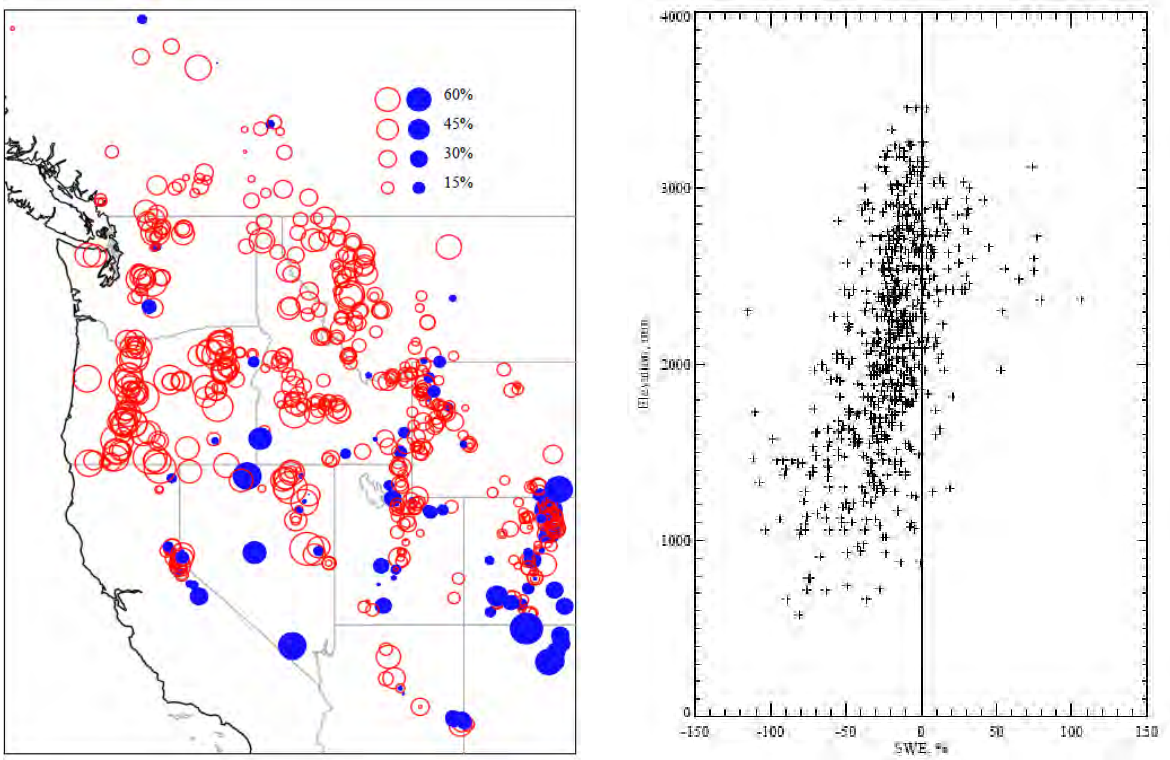
ET is the dominant hydrologic flux on the annual scale, consuming more than 70 percent of the precipitation supply. As can be seen in figure B-8, ET is highest in regions with greatest precipitation. This is not to say that the ET demand is highest in these regions, but rather that ET tends to be supply-limited in the Basin. The ET demand (potential ET [PET]) is actually higher in the warmer climate of the Lower Basin, but water supply in the form of soil moisture is less and what is available is depleted earlier than in the Upper Basin watersheds.

FIGURE B-8
Estimated Average Annual ET and Runoff (mm), April 1 SWE (mm), and Annual Average Runoff Efficiency (fraction of precipitation converted into runoff) for 1971–2000
Derived from historical VIC simulations.



Previously published research was relied on to assess observed snowpack trends in the Basin. Research by Mote (2003), Mote et al. (2008), Clark et al. (2001), Cayan et al. (2001), and Pederson et al. (2011) indicate a general decline in April 1 SWE for Pacific Northwest and northern Rocky Mountain locations, and increases in parts of the Great Basin and southern Rockies, as shown in figure B-9.

FIGURE B-9
Left panel: Linear Trends in April 1 SWE at 594 Locations in the Western United States and Canada, 1950–2000 (Mote et al., 2008) (Negative trends are shown by open circles, positive by solid circles.)
Right panel: April 1 SWE Trends (1950–2000) Plotted against Elevation of Snow Course (Mote et al., 2008) (Units on y-axis are incorrectly labeled by author as mm and should be meters.)



Widespread decreases in springtime snowpack are observed with consistent results across the lower elevation northern latitudes of the western United States. The high-elevation and thus cooler Rockies do not consistently produce decreasing trends for SWE. To assess the vertical characteristics of SWE, Mote plotted April 1 SWE trends (1950 to 2000) against elevation of snow course (figure B-9). Losses of SWE tend to be largest at low elevations and strongly suggest a temperature-related effect.

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

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

4.2.3 Climate Teleconnections

Research indicates a relationship between Pacific Ocean climate indices and Basin streamflow (Redmond and Koch, 1991; Webb and Betancourt, 1992; Cayan et al., 1999; Mo et al., 2009; and others). The June through November SOI is identified by Redmond and Koch (1991) as a strong indicator of ENSO events. For the Study, relationships between the PDO and ENSO and natural flows in the Upper Basin were examined. Figure B-10 presents the annual PDO index and indicates when June through1 November SOI average values are below -1.0 or above 1.0. The solid red bars indicate a positive PDO index, or warm PDO phase, while the solid blue bars indicate the cold PDO phase. The light red and blue shading indicate the SOI condition. Evident in this figure is the low frequency phasing of the PDO (multi-decadal scales) and the significant year-to-year variability in the ENSO events. Indicated by the line on this figure is the 11-year, center-weighted annual flow departure from long-term mean for the Colorado River at Lees Ferry, Arizona. Correlation between the low frequency PDO and decadal scale Colorado River flows appears prominent since the mid-1940s with lower decadal-scale flows during cool PDO phases and higher flows during warm PDO phases. However, significant variability exists even at these scales and prior to the mid-1940s, the correlation is poor.

There are other climate teleconnections that appear to influence multi-decadal variations in precipitation patterns (e.g., AMO) and others that can modify the characteristics of seasonal precipitation (e.g., Madden-Julian Oscillation and Arctic Oscillation) (Becker et al., 2011; Bond and Vecchi, 2003; Hu and Feng, 2010). The understanding of the influence of these teleconnections on the Colorado River precipitation, and their usefulness as an indicator, is still evolving.

FIGURE B-10
Plot of Water-Year Average PDO Values and ENSO Events Defined by SOI Averages for the Period June–November

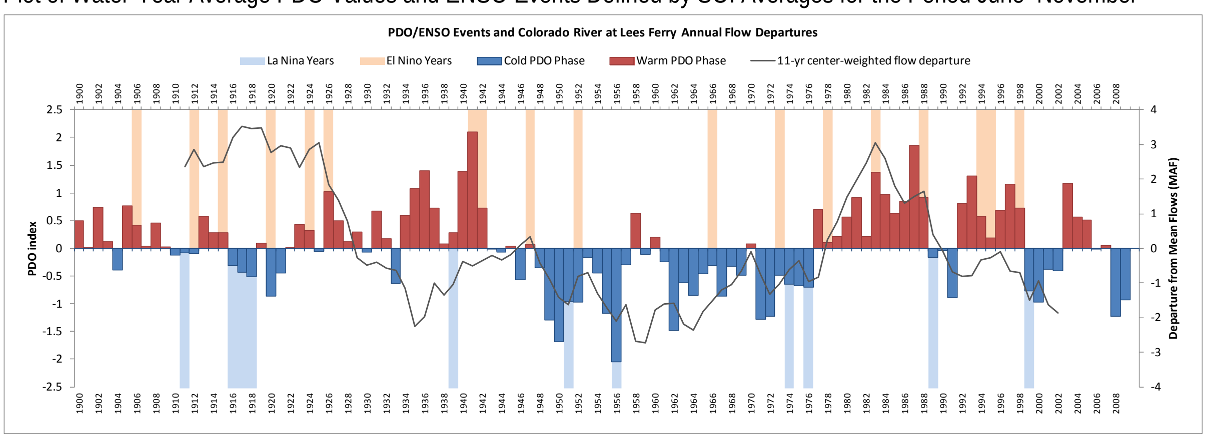
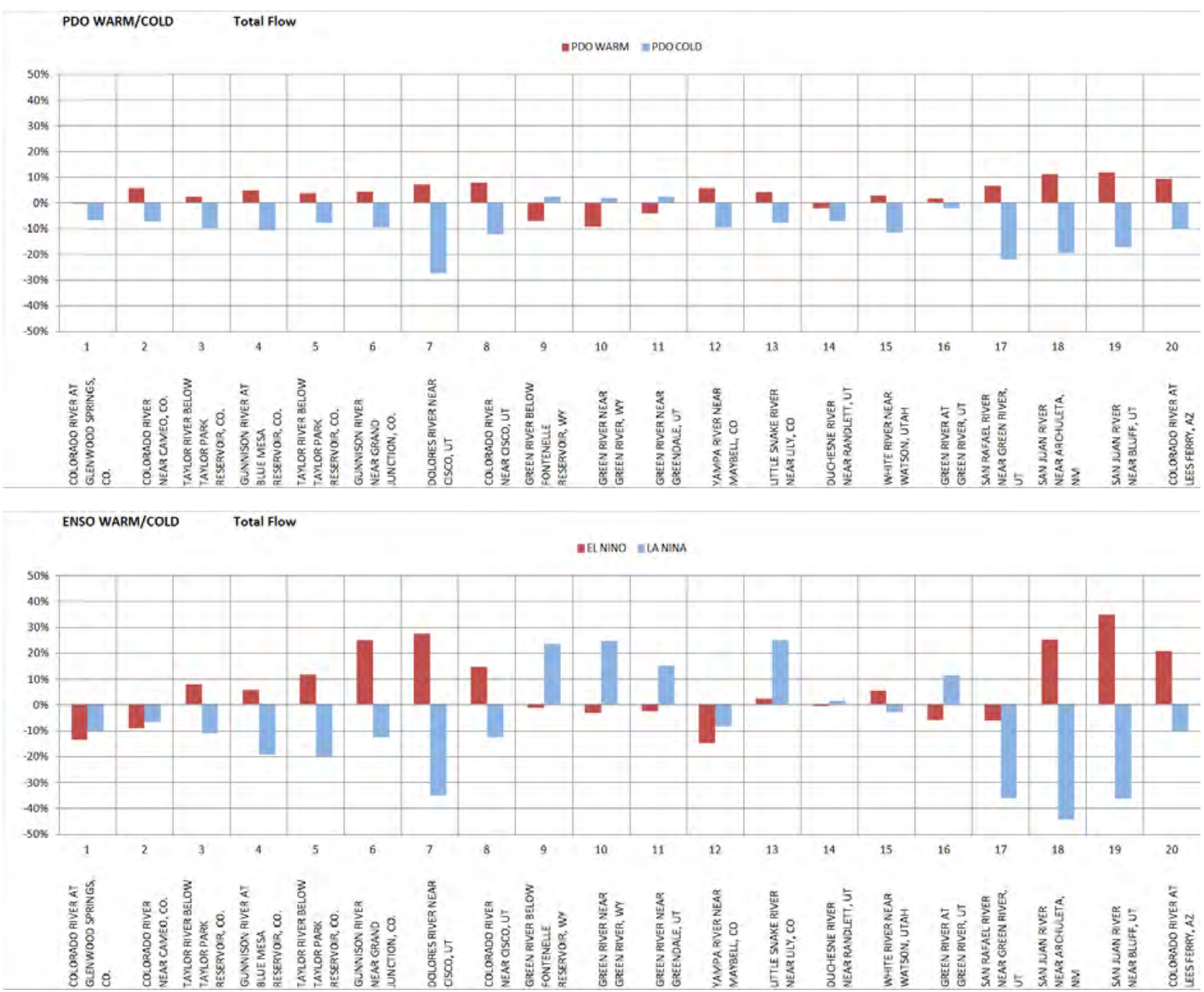


Figure B-11 illustrates water year departure from median streamflows in percent during warm and cold PDO and ENSO periods sampled from the period 1906 to 2007 for Upper Basin natural flow locations. The red bars indicate the streamflow departures for the warm phase of PDO (top) and ENSO (bottom), while the blue bars reflect the departures during the cool phases. Although significant streamflow variability exists from year to year, the majority of the flows are higher than normal during the warm PDO and ENSO (El Niño) phases. Conversely, the majority of the flows are lower than normal during the cool PDO and ENSO (La Niña) phases. It should be noted that the PDO and ENSO relationship is essentially inverted for the northern Basin in Wyoming (Green River Basin) where flows tend to be higher during the cool PDO and ENSO (La Niña) phase. The dividing line separating typical ENSO influence varies considerably from year to year, but is often referred to as a line from San Francisco to Cheyenne (Edwards and Redmond, 2005).

Overall, the natural inter-annual variability in streamflow tends to be more dominant than the relationships to either ENSO or PDO. ENSO has considerably more skill (strength as a predictor of seasonal precipitation or streamflow) in the coastal watersheds of the Pacific, than over the Basin. PDO, on the other hand, is a low-frequency signal (multi-decadal scale) that limits the number of events that could be correlated. However, it is important to note that in 2011 to 2012 the climate was entering a strong combined cool phase of both ENSO and PDO. The alignment of both signals in the cool phase suggests a propensity for continued drying trends in the coming years. The ability to predict the future state of PDO, however, is limited at this time.

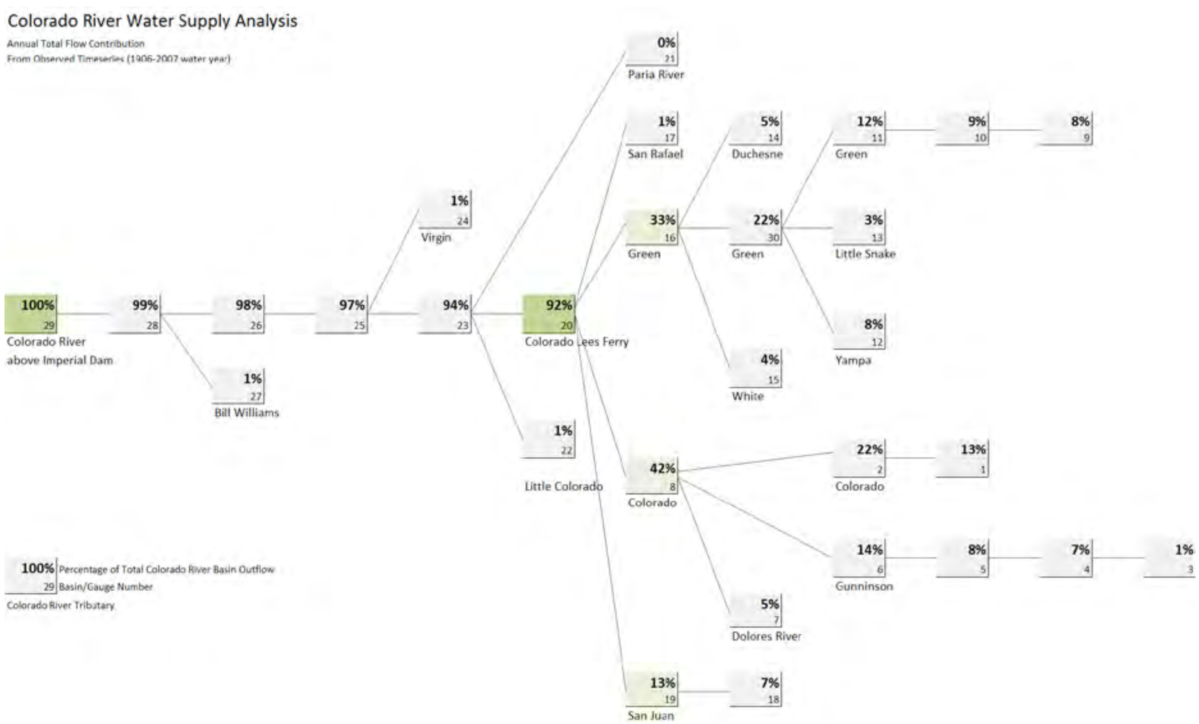
FIGURE B-11
Median Change in Flows from Long-term Average for Warm and Cold PDO (top) and ENSO (bottom) Years



4.2.4 Streamflow

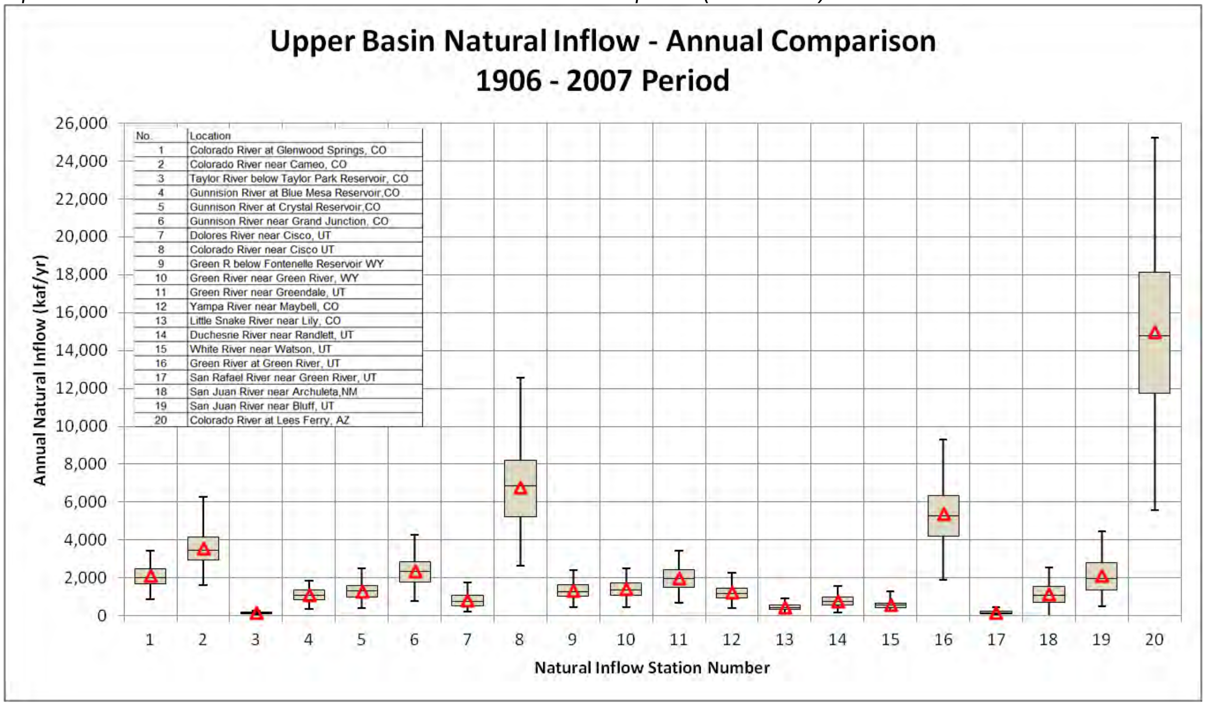
Analysis of streamflow records for the 29 natural flow locations indicated that about 92 percent of the total Colorado River at Imperial Dam, Arizona natural flow is contributed by runoff upstream of Lees Ferry, Arizona (figure B-12). As shown graphically in figure B-12, the Green River contributes about 33 percent of the total natural flow, the Colorado River at Cisco, Utah about 42 percent, and the San Juan River about 13 percent based on long-term annual natural flows from 1906 to 2007. Due to the importance of these rivers to the overall supply, they were selected as key locations for historical assessment. In addition, the Colorado River at Lees Ferry, Arizona is used because approximately 92 percent of the Basin natural flow (measured at Imperial Dam, Arizona) has accumulated there.

FIGURE B-12
Colorado River Basin Average Annual Natural Flow Contribution (% of total) for each of the 29 Natural Flow Locations
Streamflow derived from the observed period (1906–2007). See figure B-2 for names of locations.



The mean annual flows for 1906 to 2007 at each of the 20 Upper Basin natural flow locations are shown in figure B-13. Also shown is the variability of annual flows as “box-whisker” ranges. The mean annual flow of the Colorado River at Lees Ferry, Arizona (location 20) is approximately 15.0 million acre-feet (maf), but ranged from 5.6 maf (1977) to 25.2 maf (1984) over this period. The upper Colorado River at Cisco, Utah (location 8), Green River at Green River, Utah (location 16), and San Juan River at Bluff, Utah (location 19) have mean annual flows of 6.8 maf (ranging from 2.6 to 12.6 maf), 5.4 maf (ranging from 1.9 to 5.3 maf), and 2.1 maf (ranging from 0.5 to 4.5 maf), respectively.

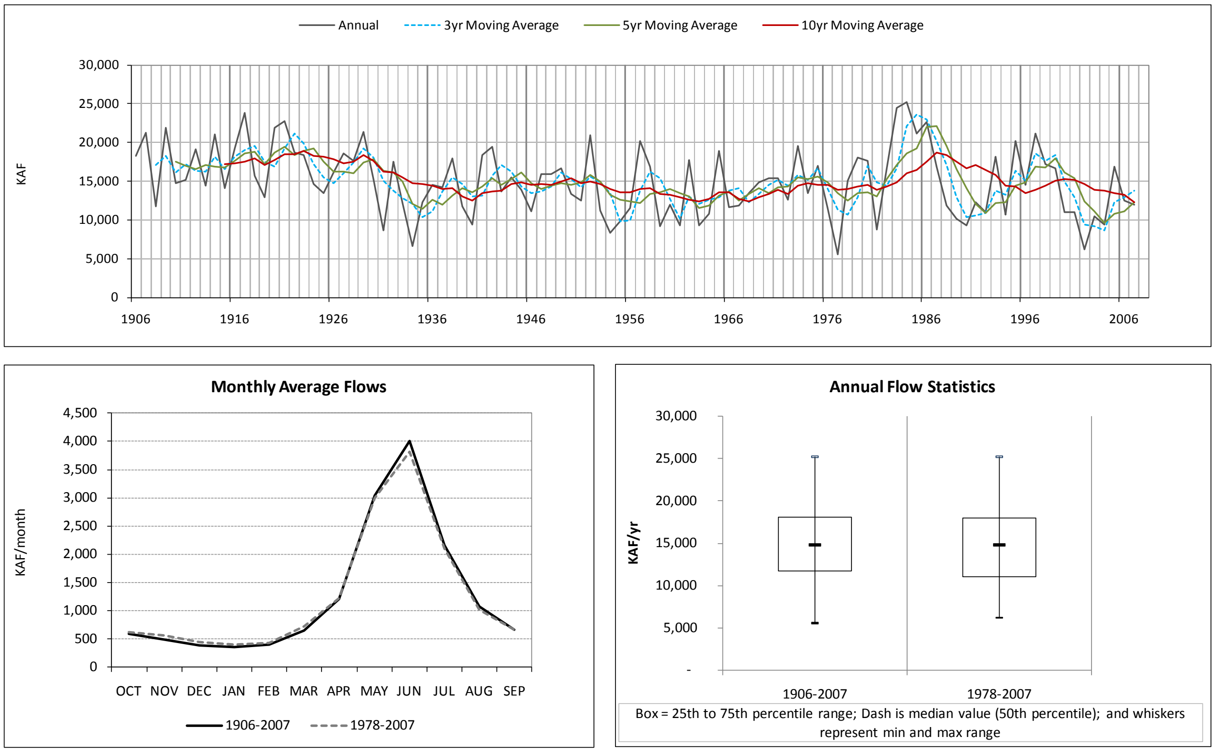
FIGURE B-13
Upper Basin Average Annual Total Natural Flows
kaf/yr = thousand acre-feet per year
Box represents the 25th, 50th, and 75th percentiles; whiskers represent the maximum (max) and minimum (min), and triangle represents the mean flow. Streamflow derived from the observed period (1906–2007).



Streamflow analysis summaries (snapshots) were prepared for all 29 natural flow locations to evaluate the trends and variability of flows. Four snapshot summaries are presented in this report for the following key locations: Colorado River near Cisco, Utah (location 8); Green River at Green River, Utah (location 16); San Juan River near Bluff, Utah (location 19); and Colorado River at Lees Ferry, Arizona (location 20). Additional streamflow analysis figures for each of the major contributing flow locations are included in appendix B5. This supplemental material includes a table reporting specific monthly streamflow averages, annual averages including minimum and maximum values with the years they occurred, and a more-detailed analysis of deficit/surplus periods.

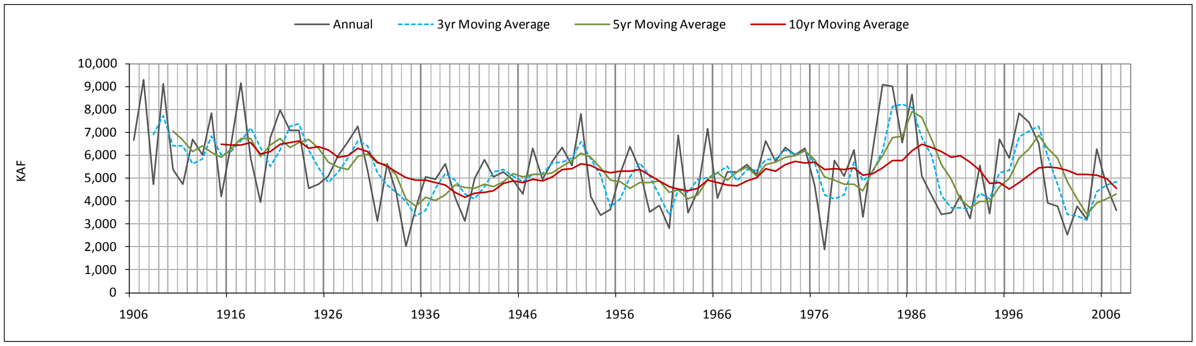
The snapshot results were developed from the natural flows dataset using data for water years 1906 to 2007 (figures B-14 to B-17). The top plot in each figure shows the annual flow volumes and the moving averages for 3, 5, and 10 years. This plot provides a visual assessment of streamflow variability, minimum and maximum flows, and long-term trends. For most selected locations, greater variability and more frequent events of greater magnitude are observed after 1976. Generally lower flows are observed from the mid 1930s to mid 1960s and a slightly downward trend in flows is observed in all locations for this time period. As an example, the Colorado River at Lees Ferry, Arizona plot (figure B-14) shows a period of generally below average streamflow and a period of moderate variability for the period 1930 to 1976. Beginning in 1977, streamflow amplitude and variability increased, with a decrease in streamflows in the most recent two decades. These recent changes in streamflow are attributed, in part, to shifts in the atmospheric-oceanic conditions as represented by PDO and ENSO and hydrologic response to recent warming.

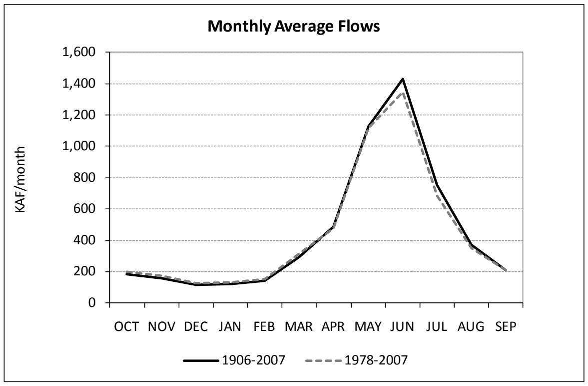
FIGURE B-14
Colorado River at Lees Ferry, Arizona Natural Streamflow Snapshot Analysis



The bottom left plot shows a two-period comparison of monthly average streamflow. The first period spans 1906 to 2007, while the second period captures the more recent 30-year period, 1978 to 2007. For the period 1978 to 2007, all selected locations exhibit a reduction in late spring streamflows and a slight increase in winter streamflows when compared to the long-term (1906 to 2007) averages. The annual mean flow was slightly lower at most of the Upper Basin locations during the 1978 to 2007 period, while annual variability, based on the inter-quartile (25th to 75th percentile) range of flows, was higher during this period. The mean annual flow for the 1978 to 2007 period is 14.6 maf—about 3 percent lower than the 1906 to 2007 period mean annual flow of 15.0 maf. The increase in variability can be explained largely by the two significant high-flow periods (the early-mid 1980s and the late 1990s) and the recent extended drought conditions during this period. The two periods show similar maximums and minimums for the 1-, 3-, and 5-year averages because the annual flow extremes (both high and low) have mostly occurred in the most recent 30-year period and are thus represented in both periods (the most recent period is also included in the long-term period).This finding is consistent with precipitation trends that show increased variability in the recent period. However, these changes are not universal. For example, the Colorado River at Cisco, Utah station shows an increase in variability in the more recent period, and also a slight increase in annual mean flow. Conversely, the San Juan River near Bluff, Utah station shows a lower mean flow, but a slightly lower variability in the recent period as compared to the longer 1906 to 2007 period. The two highest flows at this location occurred in 1941 and 1973.

FIGURE B-15
Green River at Green River, Utah Natural Streamflow Snapshot Analysis





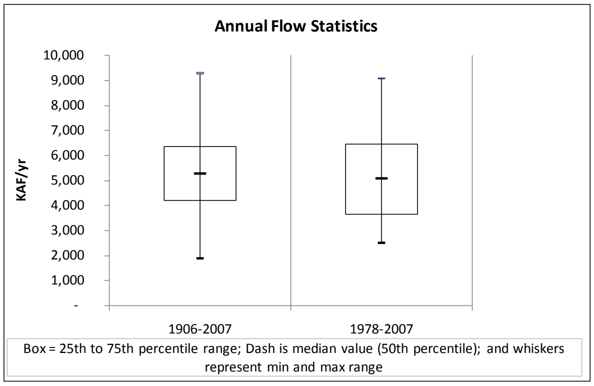
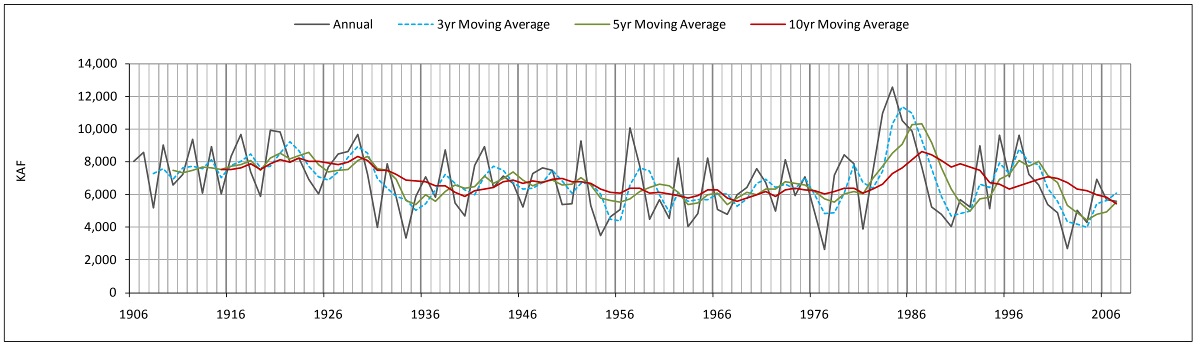
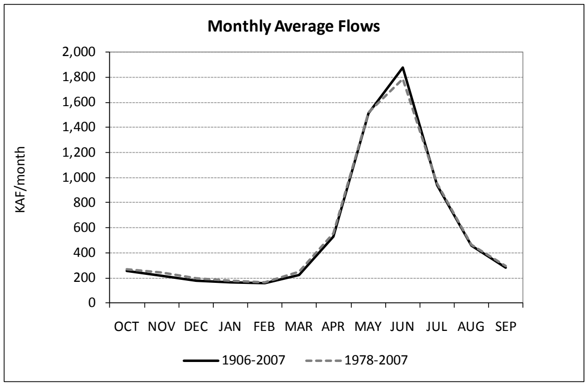


FIGURE B-16
Colorado River near Cisco, Utah Natural Streamflow Snapshot Analysis





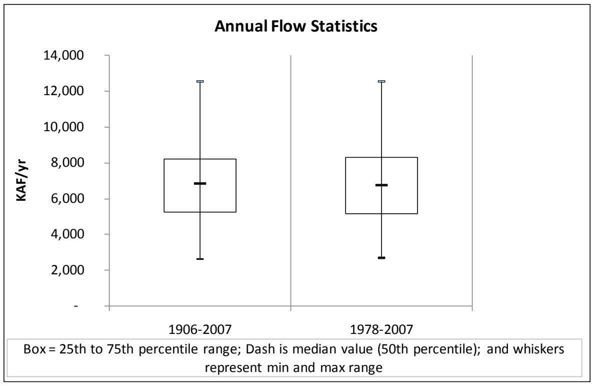
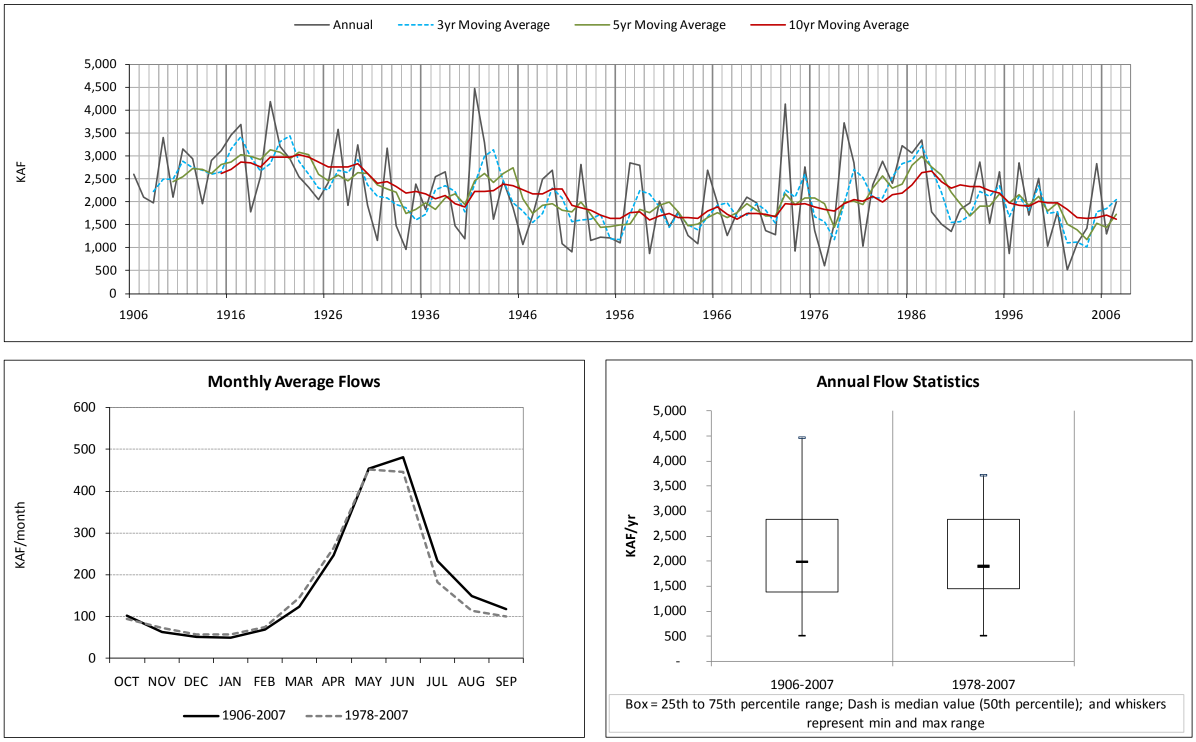


FIGURE B-17
San Juan River near Bluff, Utah Natural Streamflow Snapshot Analysis

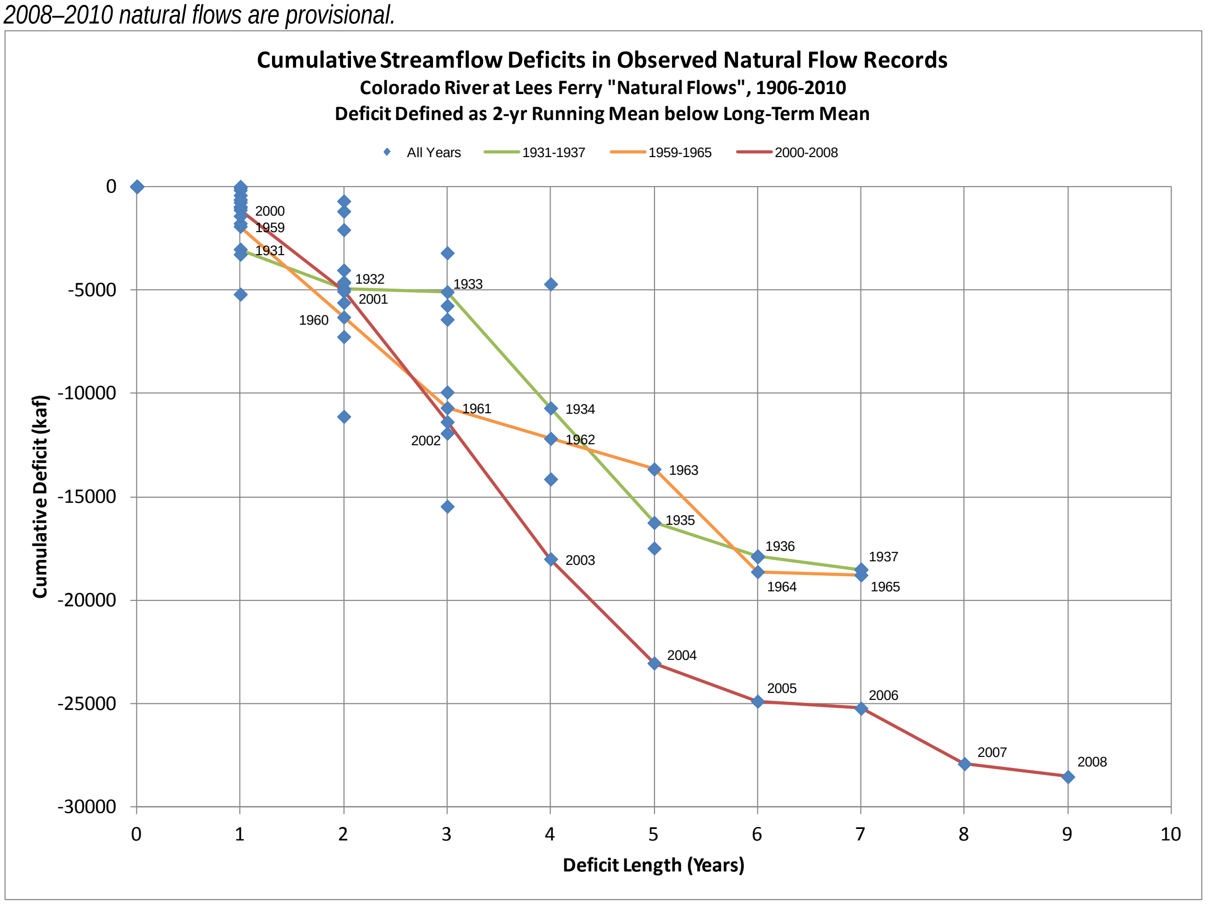


As with temperature and precipitation, Miller and Piechota (2008) also evaluated streamflow trends and explored the significance of a step change in streamflow, which occurred during the mid 1970s. The step change time series data were divided into the first 69 years of data (1906 to 1974) and the latter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

The inter-annual variability of climate and hydrology within the Basin produces frequent periods when the mean flow during that period is below the long-term mean. These occurrences are referred to as periods of streamflow deficit or deficits for the purpose of this report. As part of the analysis conducted for this report, different averaging periods for determining and measuring deficits were considered. The use of a 1-year averaging period was discarded because it implied that any 1 year above 15 maf of natural flow at Lees Ferry, Arizona, would break a multi-year deficit. The use of a 2-year averaging period implies that it may take 2 consecutive, above-normal years (or 1 extremely wet year) to end a deficit. The definition used in the remainder of this report is the following: a deficit occurs whenever the 2-year average flow falls below 15 maf, the long-term mean annual flow of the 1906 to 2007 period.

Applying this definition, figure B-18 presents the severity of 2-year deficits in the observed record. For each year of the 1906 to 2010 period[4], the 2-year running average annual flow was calculated. The difference between the 2-year running average flow and the long-term mean annual flow was computed. If the difference was negative, it was labeled "deficit" and the volumes were accumulated until the difference was once again positive. The deficit length and cumulative amount were recorded for each year. Three significant deficit spells that occurred in the observed period beginning in 1931 (7-year deficit), 1959 (7-year deficit), and 2000 (9-year deficit) are shown on the figure in green, orange, and red, respectively. As can be seen from the figure, the deficit that began in 2000 accumulated a 9-year deficit of more than 28 maf. This recent deficit is more severe than any other deficit in the observed period.

FIGURE B-18
Cumulative Streamflow Deficits (defined as 2-year running mean below 15 maf) for the Colorado River at Lees Ferry, Arizona
2008–2010 natural flows are provisional.



4 The natural flow at Lees Ferry, Arizona extended to 2010, based on provisional natural flow estimates is used here to better reflect the current state of streamflow deficit.

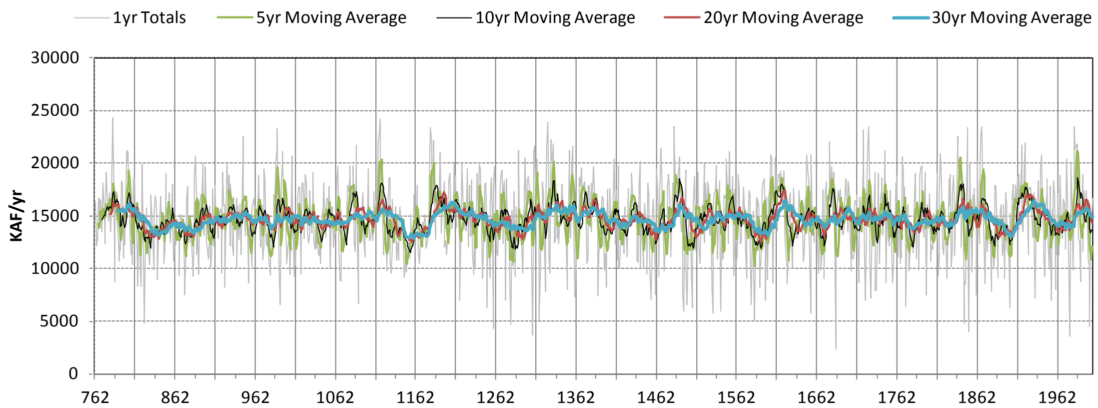
4.3 Paleo Reconstruction of Streamflow

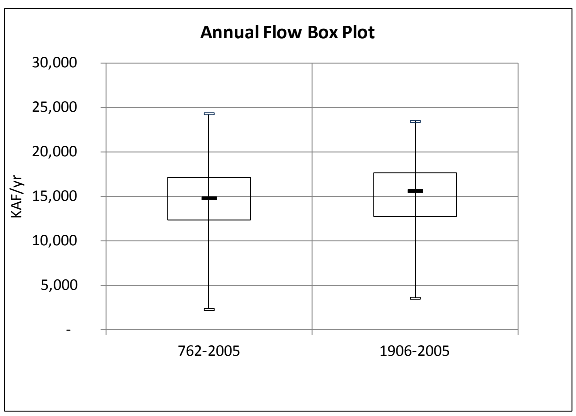
A summary of the snapshot results for Colorado River at Lees Ferry, Arizona from the paleo-reconstructed 762 to 2005 period is shown in figure B-19. The top plot shows the annual flow volumes and the moving averages for 3, 5, 10, 20, and 30 years for the period of record. This plot provides a visual assessment of streamflow variability, minimum and maximum flows, and long-term trends. Period comparisons between long-term paleo reconstruction (762 to 2005) and a segment of the observed record (1906 to 2005) are shown. The annual flow box plot shows the minimum, 75th, 50th, and 25th percentiles, and maximum annual streamflows for the two analysis periods. The minimum, 25th percentile, median, and 75th percentile are all slightly less in the paleo reconstructed record, indicating that the paleo reconstructed streamflows are lower than the observed record. Variability is increased in the paleo reconstructed record, as illustrated by the broader inter-quartile range and minimum/ maximum values. Finally, the bottom panel shows the annual (left axis) and cumulative (right axis) deviations from the mean annual flow to illustrate the wet and dry periods in this long-term record.

Streamflow deficits using the same methods as described in the previous section were similarly computed for the 762 to 2005 period and the 1906 to 2005 period, and statistics are presented in three exceedance plots (duration, magnitude, and intensity) in figure B-20. The 762 to 2005 period contains deficits that are longer in duration (16 years) and larger (as much as 35 maf) than those in the 1906 to 2005 period. Thus, the sequences of wet-dry from the much longer paleo record suggest that deficits of greater severity than the recent deficit are possible. Interestingly, the deficit intensity (defined as the cumulative deficit divided by the duration of the deficit, which can give an indication of the annual severity of deficits) is similar between the two periods, suggesting that the paleo record produces longer deficits, but that they may not be any more intense on an annual basis than the observed record.

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

FIGURE B-19
Colorado River at Lees Ferry, Arizona Paleo Streamflow Snapshot Analysis
cum=cumulative





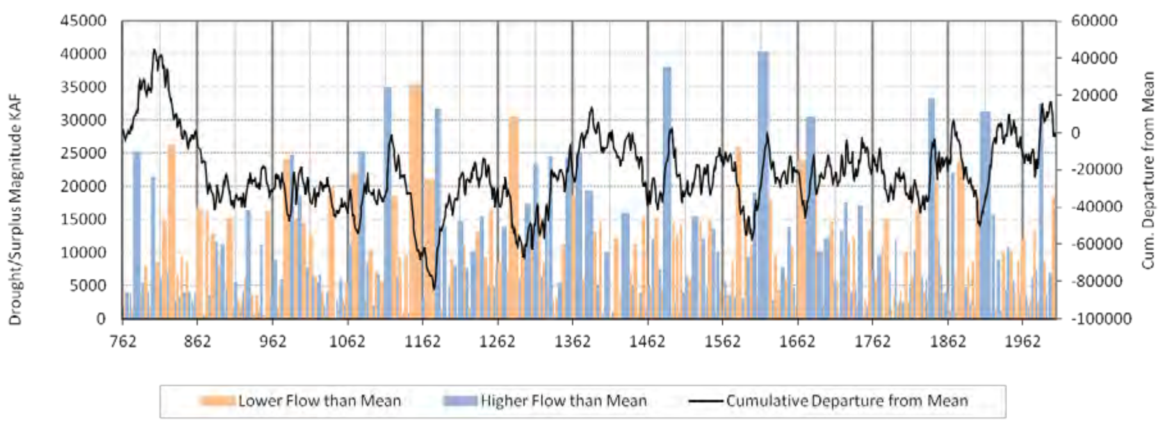
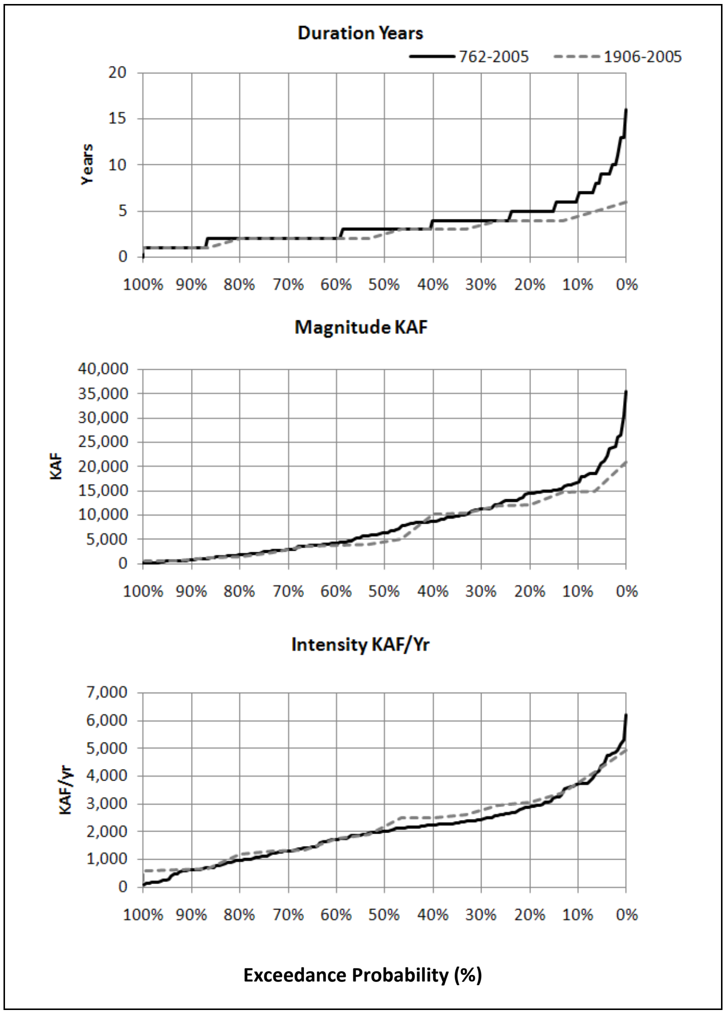


FIGURE B-20
Comparison of Drought Characteristics between a Segment of the Observed Period (1906–2005) and the Paleo Period (762–2005)



5.0 Future Supply under the Observed Resampled Scenario

5.1 Methods

Used by Reclamation in several past planning studies (such as Reclamation, 2007), the Observed Resampled[5] scenario is quantified by applying the Indexed Sequential Method (ISM) (Ouarda et al., 1997) to the 1906 to 2007 observed natural flow record to generate 102 sequences, each 50 years in length. ISM is a stochastic resampling method that creates a number of different future hydrologic sequences (or realizations). The length of the hydrologic sequence is determined by the simulation horizon (2011 to 2060, or 50 years in the Study) and the number

[5] The analysis of the Direct Natural Flow, Direct Paleo, and Nonparametric Paleo Conditioning scenarios discussed in appendix N of the 2007 Interim Guidelines Final EIS (Reclamation, 2007) are synonymous with the analysis of the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios discussed in this report, respectively.

of sequences is determined by the length of the record that is being resampled (1906 to 2007, or 102 years in this scenario). The ISM cycles through the observed record generating 102 hydrologic sequences, based on the assumption that the record "wraps around" at the end (i.e., 1960 to 2007, followed by 1906, 1907, and 1908).

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

5.2 Results

The results for the Observed Resampled scenario are presented as summary figures for annual and monthly flows at Colorado River at Lees Ferry, Arizona in figures B-21 through B-24. Because each supply scenario included multiple hydrologic sequences, there is a range associated with the flow statistics. Figure B-21 displays all of the individual 102 sequences in the Observed Resampled scenario. The sequence bolded in figure B-21 also appears in figure B-22, which is a representative trace of the 102 sequences for illustration purposes. Figure B-22 also depicts the annual range of natural flows when applying the ISM technique, and figure B-23 provides the annual statistics.

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

FIGURE B-21
Colorado River at Lees Ferry, Arizona Natural Flow for 102 Sequences for the Observed Resampled Scenario
The bolded line indicates a representative trace.

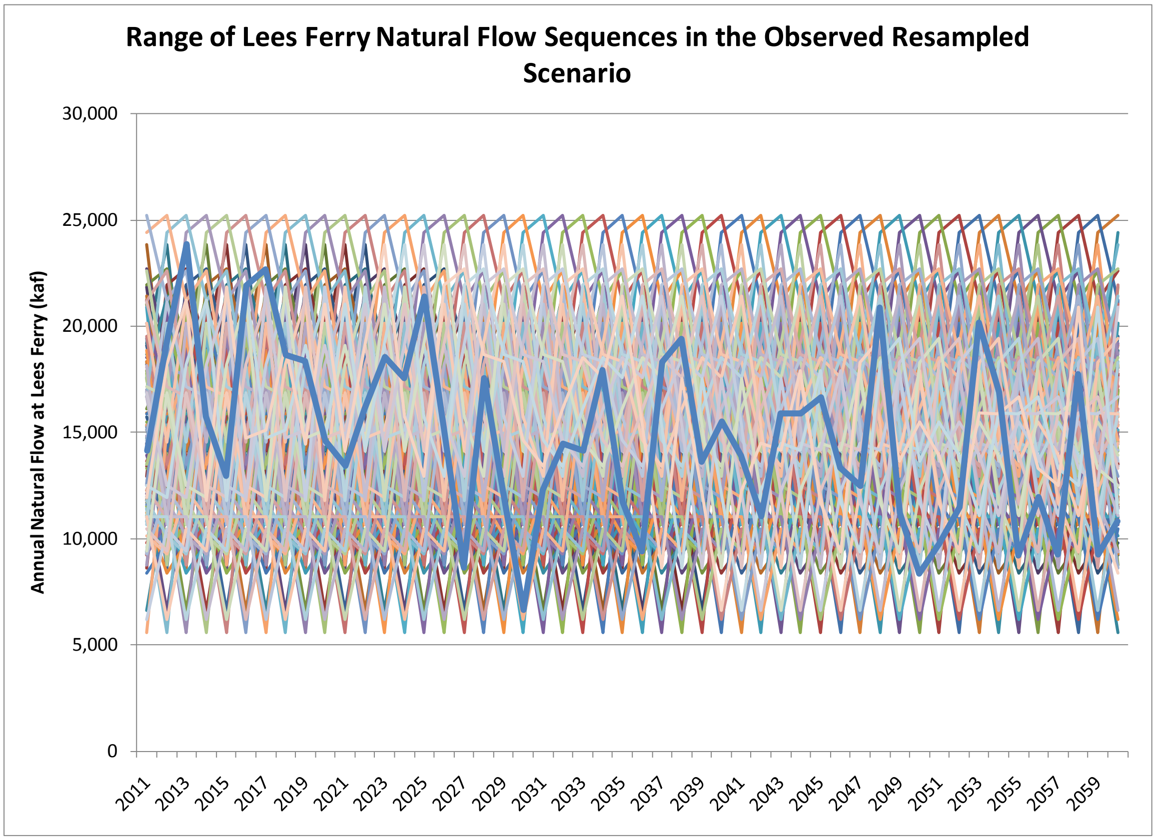


FIGURE B-22
Simulated Annual Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 102 Realizations, 2011–2060
Figure shows the median (line), 25th–75th percentile band (dark shading), 10th–90th percentile band (light shading), max/min (whiskers), and 1906–2007 observed min and max (dashed lines). The blue line indicates a representative trace.

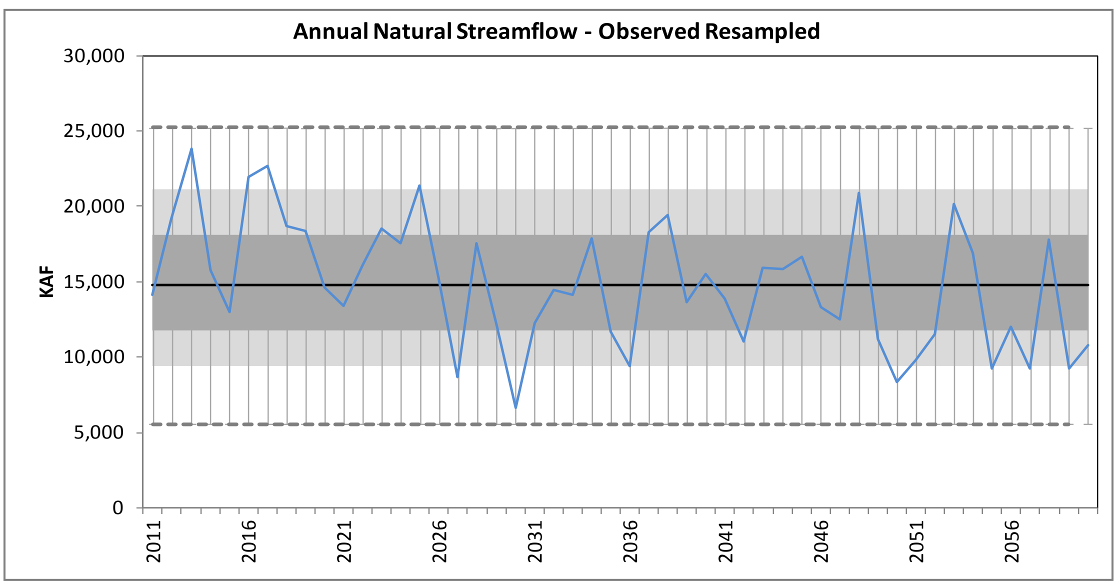
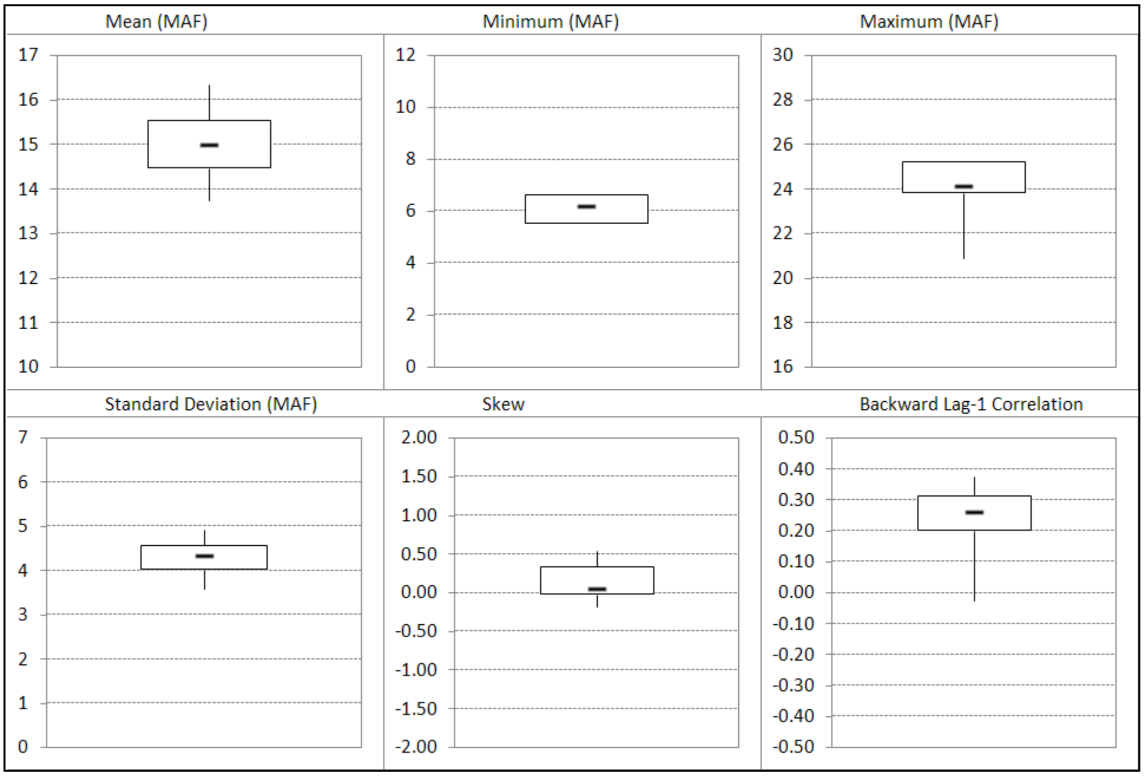
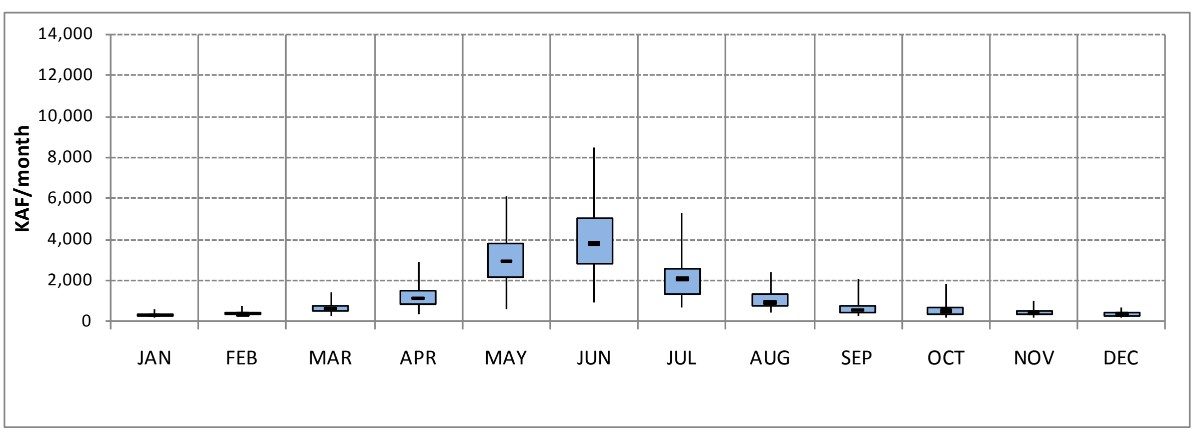


FIGURE B-23
Summary Statistics for Annual Colorado River at Lees Ferry, Arizona Natural Flows for the Observed Resampled Scenario
Figure shows the median (dash), 25th–75th percentile band (box), and max/min (whiskers).



River flow peaks in late spring due to delayed snowmelt from the higher elevation upstream watersheds, with May, June, and July exhibiting the highest flows (figure B-24). June flows are both the highest and most variable with mean monthly flows averaging about 4 maf per month and ranging from about 1 to 9 maf per month. Late summer and fall flows are considerably lower and exhibit significantly less variability.

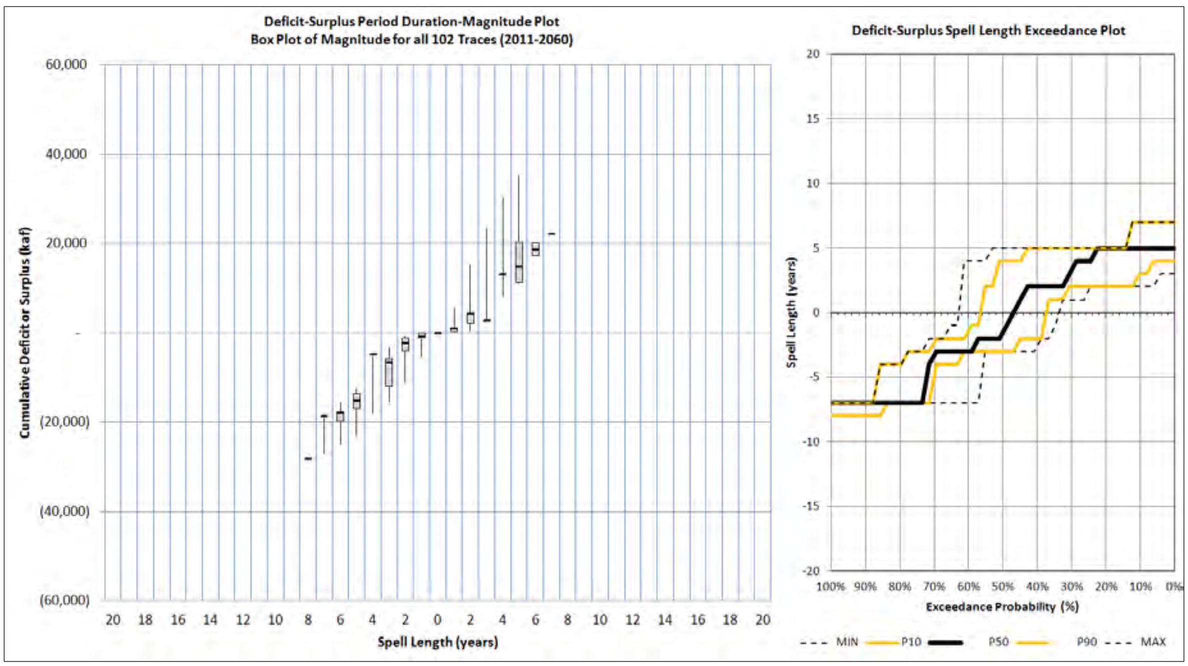
FIGURE B-24
Simulated Monthly Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 102 Realizations, 2011–2060
Figure shows the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).



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

Figure B-25 illustrates four characteristics of deficit and surplus spells throughout the Study period (2011 to 2060): spell length, spell magnitude, the frequency of specific spell lengths occurring, and the relationship between deficits and surpluses in the scenario. Box plots displaying spell length are shown in the left figure (deficit, below the x-axis, and surplus, above the x-axis). The exceedance plot shown in the right figure displays the exceedance probabilities for spell lengths. Probabilities for deficit spells are shown in the bottom half of the plot. Probabilities for surplus spells are shown in the top half of the plot.

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



Spell length: the maximum deficit is 8 years (note that this length would be 9 years if the observed record extended through 2010), and the maximum surplus is 7 years. This information is provided in both the box plots and the exceedance plot.

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

Frequency of specific spell lengths occurring: the exceedance plot inset provides information regarding the frequency of the length of deficit and surplus spells. As such, the median exceedance probability of a deficit spell of 5 years is about 70 percent, meaning there is about a

30 percent chance of a deficit longer than 5 years. Similarly, at the 30 percent median exceedance probability is a surplus spell of 3 years, meaning there is about a 30 percent chance of a surplus period lasting more than 3 years.

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

6.0 Future Supply under the Paleo Resampled Scenario

6.1 Methods

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

Because the paleo flow data are only available at the annual time step for a single location (Colorado River at Lees Ferry, Arizona), annual flows at this location were disaggregated, spatially and temporally, throughout the Upper Basin natural flow locations using a non-parametric disaggregation method (Nowak et al., 2010). The disaggregation method relies on the observed record to model the spatial and temporal distribution properties of the monthly and annual flow. Disaggregated flows at the Lower Basin natural flow locations are generated by selecting an “analog” year from the observed record. These methods have been demonstrated to be appropriate and effective for the Basin and time step. For a more detailed explanation of these methods, please see Nowak et al., 2010, and appendix N of the 2007 Interim Guidelines Final EIS (Reclamation, 2007).

6.2 Results

The results for the Paleo Resampled scenario are presented as summary figures for annual and monthly flows for the Colorado River at Lees Ferry, Arizona in figures B-26 through B-29. As with the Observed Resampled scenario, multiple realizations are simulated, producing a range associated with the flow statistics. Figure B-26 displays all of the individual 1,244 sequences in the Paleo Resampled scenario. The sequence bolded in figure B-26 also appears in figure B-27, which is a representative trace of the 1,244 sequences for illustration purposes. Figure B-27 also depicts the annual range of natural flows, while figure B-28 provides the annual statistics.

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

FIGURE B-26
Colorado River at Lees Ferry, Arizona Natural Flow for 1,244 Sequences for the Paleo Resampled Scenario
The bolded line indicates a representative trace.

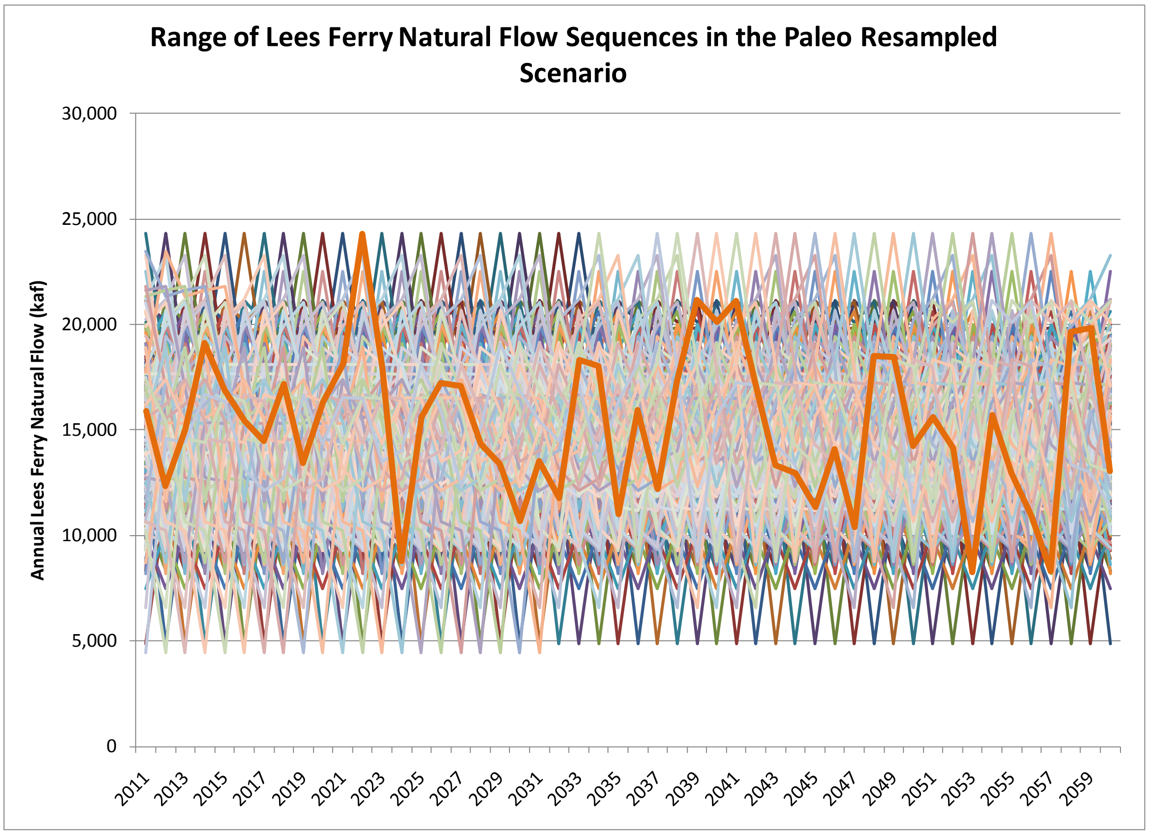


FIGURE B-27
Simulated Annual Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 1,244 Traces, 2011–2060
Figure shows the median (line), 25th–75th percentile band (dark shading), 10th–90th percentile band (light shading), max/min (whiskers), and 1906–2007 observed min and max (dashed lines). The orange line indicates a representative trace.

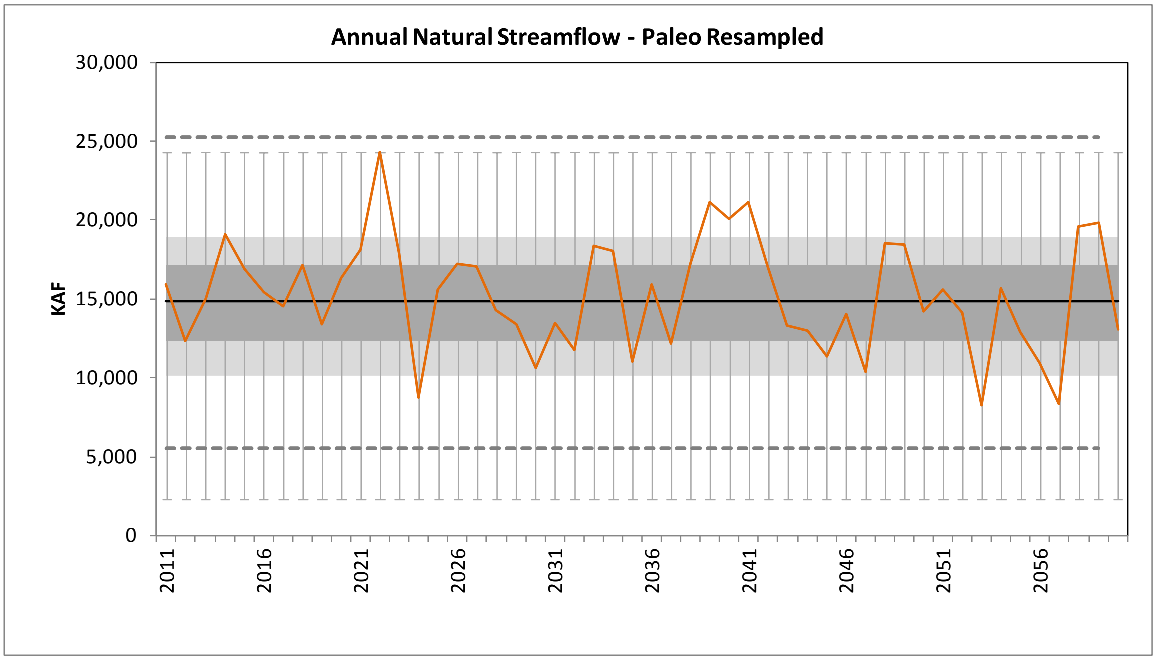
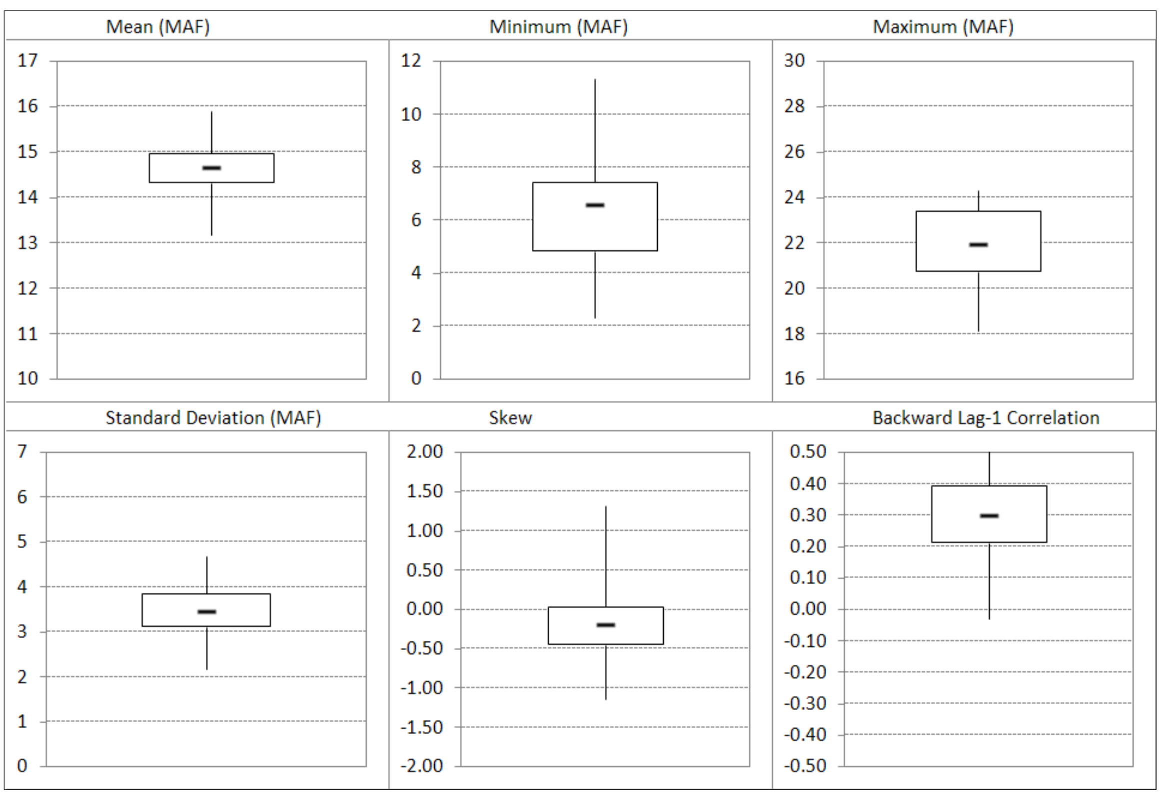


FIGURE B-28
Summary Statistics for Annual Colorado River at Lees Ferry, Arizona Natural Flows for the Paleo Resampled Scenario
Figure shows the median (dash), 25th–75th percentile band (box), and max/min (whiskers).



Monthly river flows suggest no significant change from the Observed Resampled scenario. Peak flows occur in late spring, with May, June, and July exhibiting the highest flows (figure B-29). As in the Observed Resampled scenario, June flows are both the highest and most extreme, with mean monthly flows averaging about 4 maf per month and ranging from about 1 to 9 maf per month. This was expected because the disaggregation applied to the annual paleo reconstruction was trained on the observed natural flow data. Also similar to the Observed Resampled scenario, late summer and fall flows are considerably lower and exhibit significantly less variability.

FIGURE B-29
Simulated Annual Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 1,244 Realizations, 2011–2060
Figure shows the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).

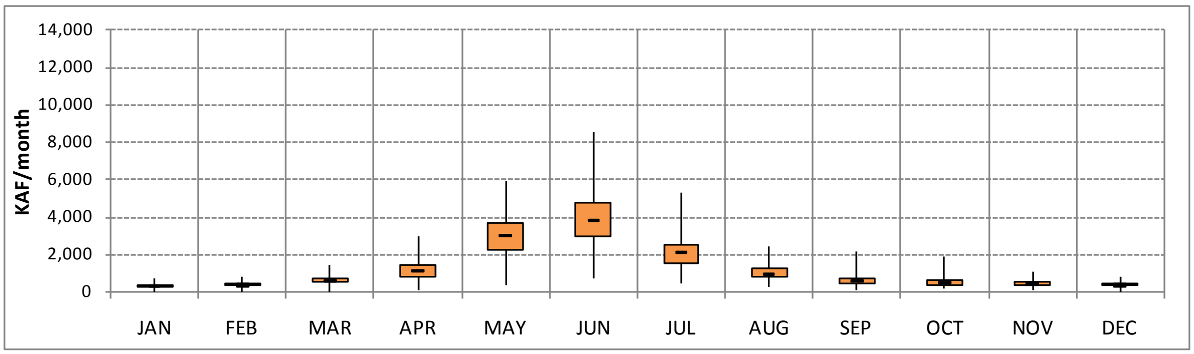
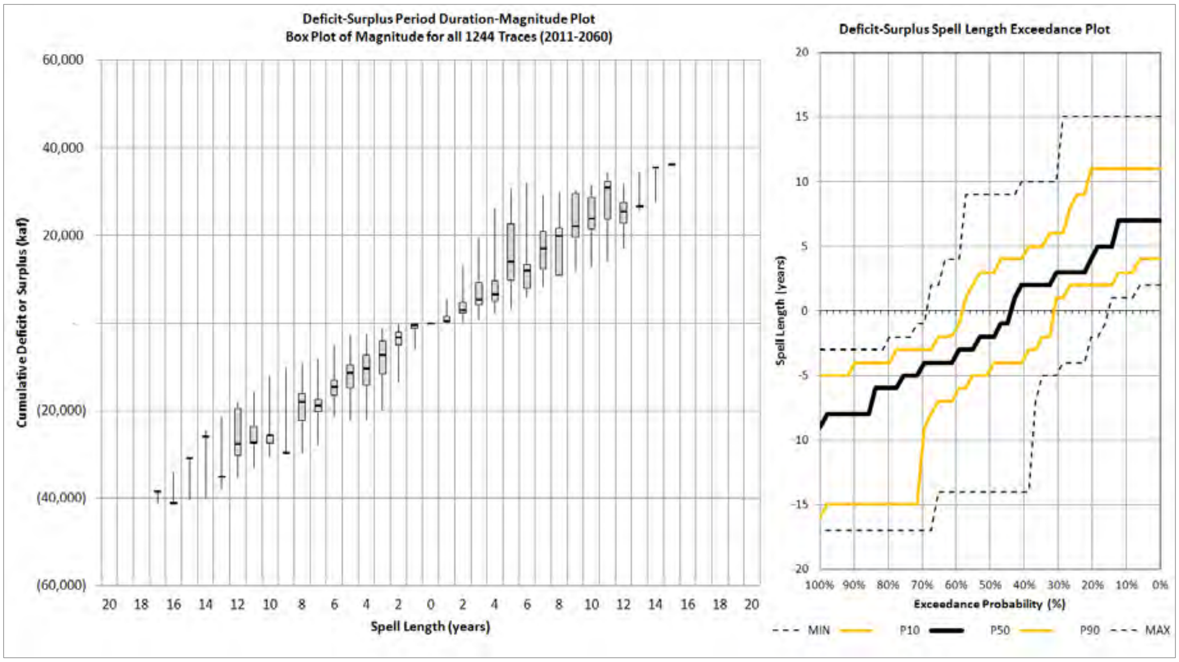


Figure B-30 illustrates the length, magnitude, and frequency of deficit and surplus spells. Under the Paleo Resampled scenario, maximum deficit and surplus periods are significantly longer in duration than those in the Observed Resampled scenario. Maximum deficit spell length under the Paleo Resampled scenario is about 17 years, and the maximum surplus spell length is about 15 years. The 17-year deficit period contains approximately 35 maf of total deficit. For comparison, the recent deficit persisted for 9 years (through 2008) with an accumulated deficit of about 29 maf. Thus, from a measure of deficit intensity, although the deficit is sustained longer in the Paleo Resampled scenario, the annual deficits are not dissimilar from the Observed Resampled scenario.

FIGURE B-30
Simulated Deficit and Surplus Spell Length and Magnitude for all 1,244 Realizations in the Paleo Resampled Scenario
Box plots show the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).



7.0 Future Supply under Paleo Conditioned Scenario

7.1 Methods

The Paleo Conditioned scenario is generated by applying a non-parametric technique to “blend” the observed historical and paleo reconstructed records to generate 1,000 traces, each 50 years in length. Flow magnitudes vary significantly across multiple reconstructions for a particular site (Stockton and Jacoby, 1976; Hildalgo et al., 2009; Hirschboeck and Meko, 2005; Woodhouse et al., 2006). However, the paleo hydrologic state agreement (i.e., wet or dry) is quite reliable across different reconstructions (Woodhouse et al., 2006).

The paleo conditioned technique blends the rich variety of drought/surplus found in the paleo reconstruction with reliable magnitudes from the observed natural flow data by first extracting a sequence of years represented simply as wet or dry from the streamflow reconstruction. Flow magnitudes are then conditionally resampled from the observed record for each year in the sequence, based on the current and previous hydrologic state. Thus, any underlying relationship between magnitude and sequencing is preserved while circumventing issues associated with magnitude reliability. For example, if an observed flow value occurred as the first year of a drought, it can only be assigned to a “dry state year” that was preceded by a “wet state year” as part of a paleo conditioned trace. Similarly, if an observed flow magnitude was the second year of a multi-year surplus period, that value can only be assigned to a “wet state year” that was preceded by another “wet state year.” This logic holds true for all wet/dry sequencing combinations. Following this method, a wealth of traces can be generated (at least 1,000 are recommended to limit sample variability) by simply changing the initial wet/dry sequence information extracted from the paleo data. Different from the ISM technique, the number of sequences is not limited to the length of the streamflow record being resampled. For a more detailed explanation of the method, see appendix N of the 2007 Interim Guidelines Final EIS (Reclamation, 2007) and Prairie et al., 2008. As was the case with the Paleo Resampled scenario, the Paleo Conditioned scenario introduces considerable variability when compared with the observed data, yet maintains the reliability of the observed magnitudes. Paleo conditioned traces were also generated at the annual time scale for Colorado River at Lees Ferry, Arizona and required the same disaggregation process employed for the Paleo Resampled scenario in order to produce monthly data at multiple locations.

7.2 Results

The results for the Paleo Conditioned scenario are presented as summary figures for annual and monthly flows at Colorado River at Lees Ferry, Arizona in figures B-31 through B-34. Figure B-31 displays all of the individual 1,000 sequences in the Paleo Conditioned scenario. The sequence bolded in figure B-31 also appears in figure B-32, which is a representative trace from the 1,000 sequences. Figure B-32 depicts the annual range of natural flows, and figure B-33 provides the annual flow statistics.

Annual natural flows are generally in the range of 5 to 25 maf, with a mean of approximately 14.9 maf. The annual statistics are similar to the Observed Resampled scenario, largely due to the paleo conditioned technique that borrows the magnitudes from the observed record when combining with state information from the paleo reconstructions. Similarly, the standard deviation, skew, and backward lag correlation indicate that the annual flow statistics are similar to the Observed Resampled scenario. Monthly flows are also similar in pattern and magnitude to the Observed Resampled and Paleo Resampled scenarios, as shown in figure B-34.

The most significant difference between the Paleo Conditioned scenario and the Observed Resampled and Paleo Resampled scenarios is in the inter-annual variability and persistence of streamflow states (wet and dry). Figure B-35 illustrates the frequency, length, and magnitude of deficit and surplus spells. Deficit periods of 15 years or longer are observed in this scenario and produce accumulated deficits greater than 60 maf. Similarly, extended surplus periods of similar length produce surpluses greater than 60 maf. Under this scenario, deficit periods could persist considerably longer than the Observed Resampled and produce deficits almost twice as large. However, interestingly, the median probability of exceeding a deficit spell of greater than 7 years is only 20 percent, and there is only a 10 percent likelihood of exceeding a 5-year surplus period.

FIGURE B-31
Colorado River at Lees Ferry, Arizona Natural Flow for 1,000 Sequences for the Paleo Conditioned Scenario
The bolded line indicates a representative trace.

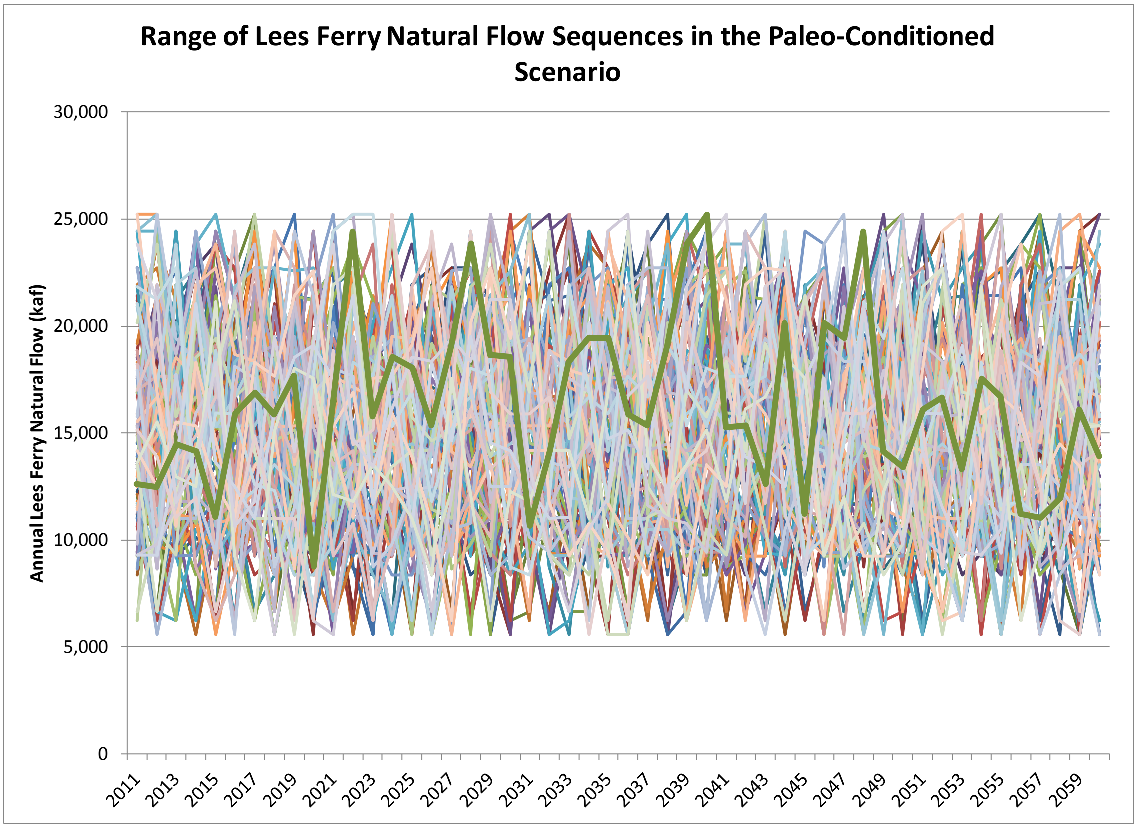


FIGURE B-32
Simulated Annual Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 1,000 Realizations, 2011–2060
Figure shows the median (line), 25th–75th percentile band (dark shading), 10th–90th percentile band (light shading), max/min (whiskers), and 1906–2007 observed min and max (dashed lines). The bolded line indicates a representative trace.

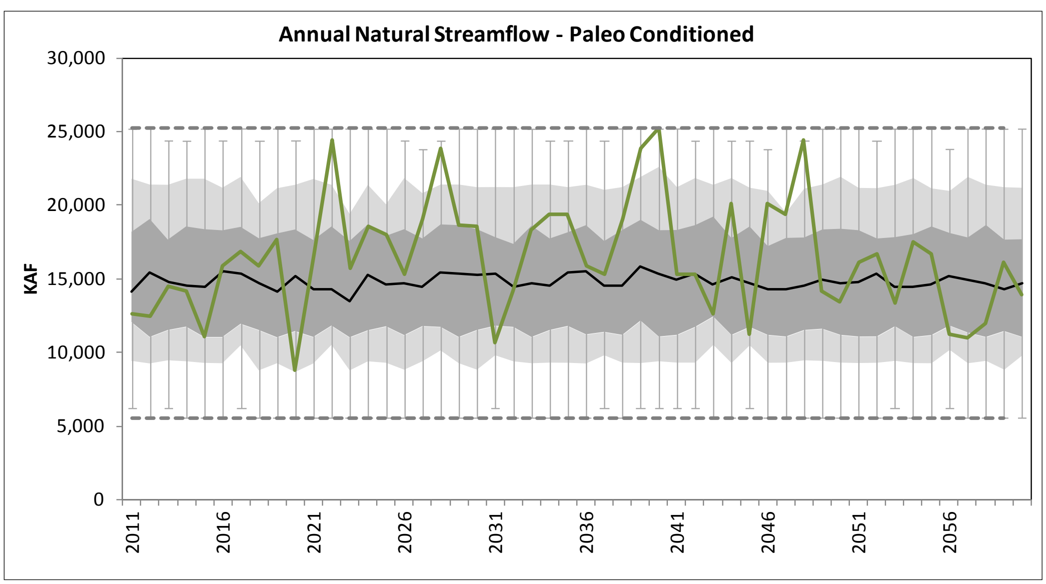


FIGURE B-33
Summary Statistics for Annual Colorado River at Lees Ferry, Arizona Natural Flows for the Paleo Conditioned Scenario
Figure shows the median (dash), 25th–75th percentile band (box), and max/min (whiskers).

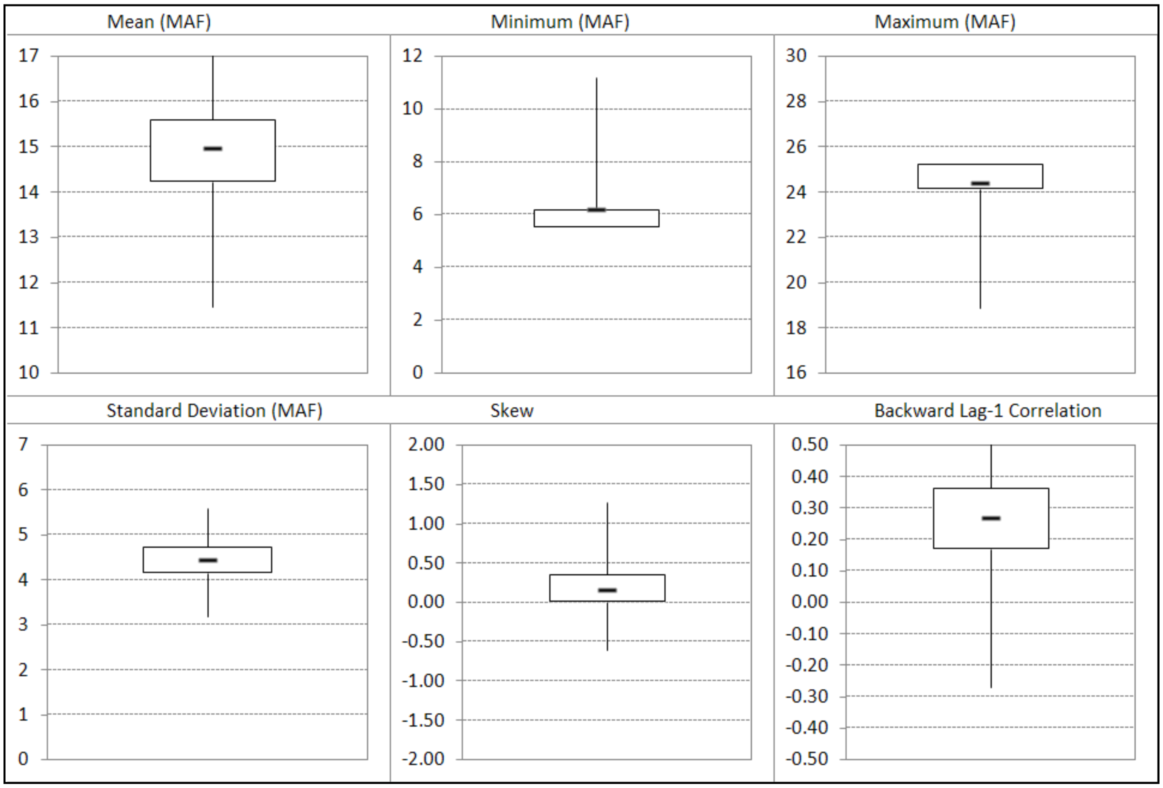


FIGURE B-34
Simulated Annual Colorado River at Lees Ferry, Arizona Natural Flow Statistics for 1,000 Realizations, 2011–2060
Figure shows the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).

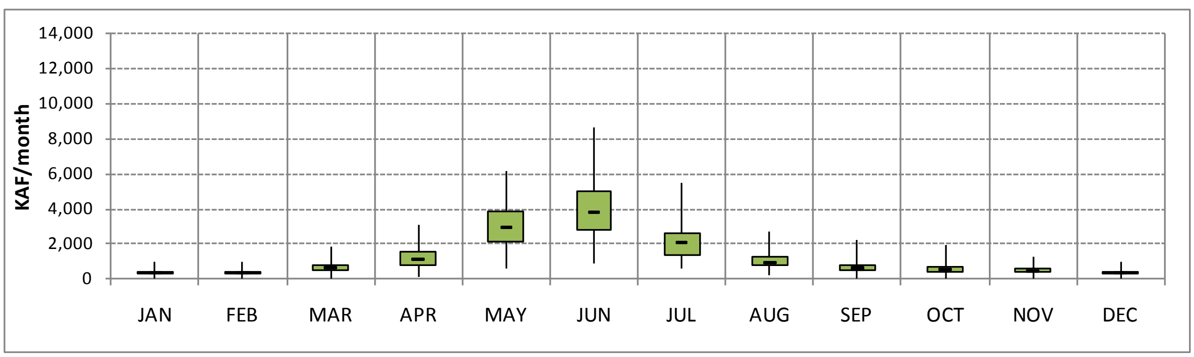
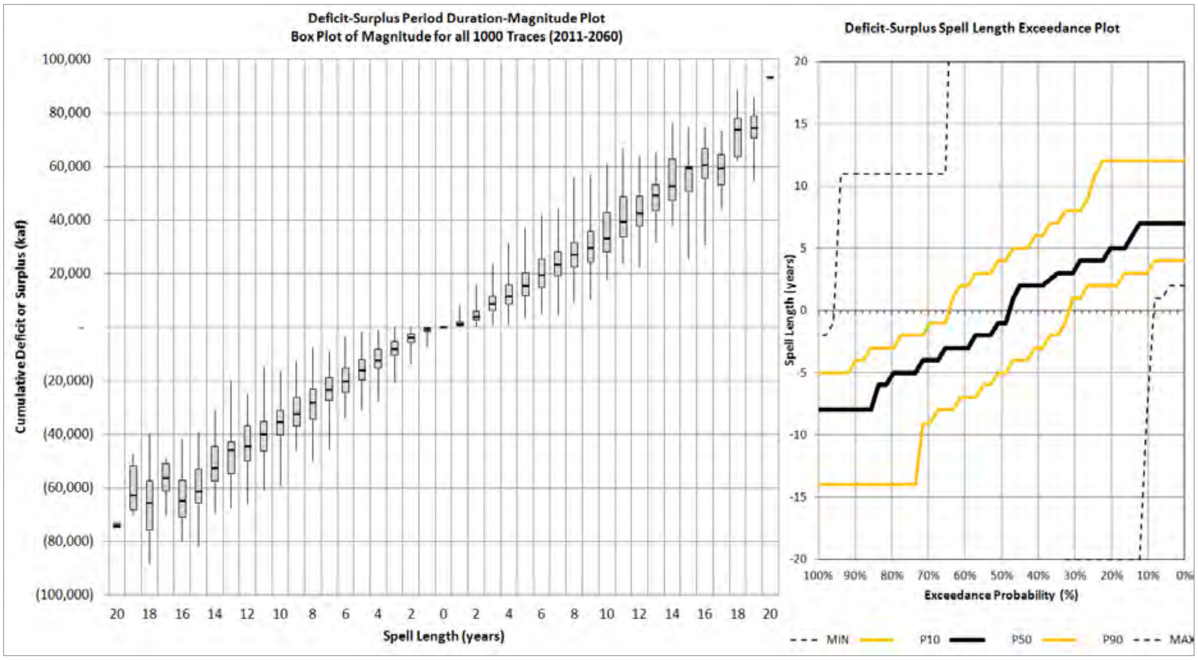


FIGURE B-35
Simulated Deficit and Surplus Spell Length and Magnitude for all 1,000 Realizations in the Paleo Conditioned Scenario
Box plots show the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).



8.0 Future Supply under the Downscaled GCM Projected Scenario

8.1 Methods

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

A number of methods for incorporating climate information in planning studies are available and have been summarized by Reclamation (2007) and others (Hamlet et al., 2010). Methods range from simple adjustments to the temperature and precipitation inputs (Delta method), to application of regional climate models for weather generation, to bottom-up risk-based approaches targeting system vulnerabilities. No one approach is better than the other; rather, each serves a specific planning purpose and consists of a set of analysis tools. The approach taken in the Study incorporates future climate information from GCMs, subsequently bias corrected and statistically downscaled, to drive a hydrologic model of the Basin. The hydrologic model simulates the effects of future climate on hydrologic processes in the Basin and provides information relating to streamflow at all major inflow points to the Colorado River and tributaries. The streamflow and ET information is then used as input into CRSS, Reclamation’s primary Basin-wide simulation model used for long-term planning studies. This approach is shown graphically in figure B-36. Using this approach of linking global and regional climate information, physically based hydrologic processes, streamflow routing, and systems modeling allows for a consistent linkage between climate and system responses that are desired as part of this scenario and the overall study of future Basin reliability. The methodological approach to develop the Downscaled GCM Projected scenario consists of five major elements depicted graphically in figure B-36. A total of 112 future climate projections used in the IPCC Fourth Assessment Report (2007), subsequently bias corrected and statistically downscaled, were obtained from the Lawrence Livermore National Laboratory under the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) (Maurer et al., 2007)[6]. These data were incorporated in the first three elements of the approach in figure B-36.

Each of the 112 downscaled climate projections was then used as input into the VIC hydrology model. The VIC hydrology model used the climate projections along with land cover, soils, elevation, and other watershed information to simulate hydrologic fluxes. The hydrologic fluxes were then routed to each of the 29 natural flow locations using a routing network derived from the topography (Lohmann et al., 1996; Lohmann et al., 1998). The result of this approach was 112 unique sequences of natural flow under future climate projections. Notably, the simulated natural flows can contain significant monthly and annual biases when compared to the natural flows of the historical period. These biases are generally small for mainstem Colorado River locations, but can be large for smaller watersheds and in areas where the VIC model was not specifically calibrated. To account and compensate for these biases, the VIC-simulated streamflows for both the historical and future periods were first adjusted for biases before incorporating into systems modeling. Details on the methods used to correct for biases are included in appendix B4.

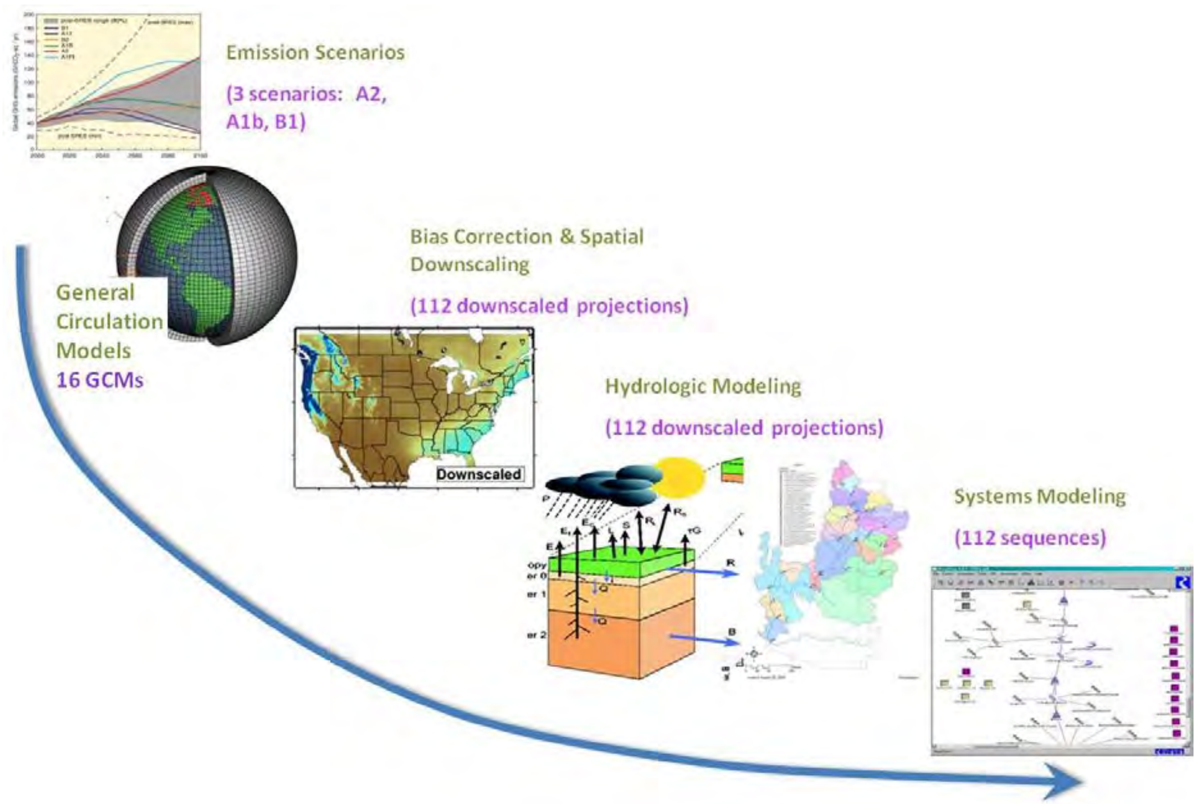
The same Downscaled GCM Projected scenario was also employed to develop the results described in the *SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011* (Reclamation, 2011c) Report. The SECURE Report was prepared by Reclamation's Office of Policy and Administration and includes projections of how climate change may impact the water supply on the Basin. The SECURE Report was prepared by Reclamation to provide consistent, reconnaissance-level information focused on the future risks to water supply throughout the eight Reclamation basins.

While the results are consistent between this report and the SECURE Report, the SECURE Report was limited to the evaluation of the meteorological and hydrologic changes under projected climate change. The Study also considered how hydrological changes may impact the performance of the Colorado River system through CRSS modeling. The differences in study objectives led to some differences in approach. The methodological differences consist primarily of the application of a streamflow bias correction method before using the simulated natural flows in the CRSS model. Reporting differences between this report and the SECURE Report consist of the selection of baseline climate conditions and the future analysis periods. Specifically, the SECURE Report computed future decadal changes from a 1991 to 2000 baseline condition, whereas the streamflow change statistics reported here were computed between the long-term historical record (1906 to 2007) and the Study period of 2011 to 2060. This period provides a long-term record consistent with that used in the Observed Resampled

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

scenario, captures a sufficiently long period necessary to describe drought and surplus statistics, and represents a mean annual flow of importance to Colorado River management. The 1906 to 2007 mean annual flow for the Colorado River at Lees Ferry, Arizona is 15.0 maf; the mean annual flow is 15.5 maf for the 1971 to 2000 period, 15.0 maf for the 1978 to 2007 period, 15.3 maf for the 1991 to 2000 period, and 14.6 maf for the 1950 to 1999 period. The 1950 to 1975 period contained lower annual flows and lower interannual variability than many of the other periods, likely influenced by conditions associated with the cold phase of PDO. To capture the projected future trends in streamflow changes associated with the Downscaled GCM Projected scenario, additional information has been provided in this report for three future 30-year time periods (2011 to 2040, 2041 to 2070, and 2066 to 2095). While the last of these periods extends beyond the Study period, it provides an important reference for understanding the potential direction of the future Basin hydrology. Therefore, results between the Study and the SECURE Report are not identical; however, work from the Study will be used to inform future reports under the SECURE Water Act.

FIGURE B-36
Methodological Approach for the Development of the Downscaled GCM Projected Scenario



8.1.1 Emission Scenarios

As discussed previously, the downscaled climate projections were obtained from the World Climate Research Program's CMIP3 database. This database includes downscaled climate projections from 16 different GCMs simulated with three different IPCC emission scenarios (IPCC, 2000). The emission scenarios are those from the *Special Report on Emissions Scenarios* (SRES) (IPCC, 2000), emission scenarios A2 (high), A1B (medium), and B1 (low), and reflect a range of future greenhouse gas (GHG) emissions. The A2 scenario is representative of high population growth, slow economic development, and slow technological change. It is characterized by a continuously increasing rate of GHG emissions, and features the highest annual emissions rates of any scenario by the end of the 21st Century. The A1B scenario features a global population that peaks mid-century and rapid introduction of new and more efficient technologies balanced across both fossil- and non-fossil intensive energy sources. As a result, GHG emissions in the A1B scenario peak around mid-century. Last, the B1 scenario describes a world with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. GHG emission rates in this scenario peak prior to mid-century and are generally the lowest of the scenarios.

SRES emission scenarios exist that have both higher (A1FI) and lower (A1T) GHG emissions than those considered in the Study (see appendix B2). However, the three scenarios included in the analysis span the widest range available for which consistent, comprehensive GCM modeling has been performed and for which downscaled climate information is available. Furthermore, while it is possible that higher rates of warming and resulting effects on streamflows are possible, it should be noted that the atmospheric response to emission increases is not immediate. Climate response to increases in GHG emissions is on the decadal scale. Uncertainty in the projected climate system response due to increased emissions (GCM uncertainty) tends to be a greater determinant of the range of climate conditions through mid-century than the uncertainty associated with future emission scenarios themselves.

Assumptions related to parameter characteristics included in the SRES emission scenarios (such as high population growth and slow economic development) are not related to parameter characteristics of the Water Demand scenarios (see *Technical Report C – Water Demand Assessment*) because they describe a global set of drivers rather than those directly associated with the Colorado River. When considering water demand scenarios combined with water supply scenarios that incorporate climate change, outdoor water demands and reservoir evaporation rates were modified to reflect estimates of changes in ET and open water surface evaporation rates consistent with the assumptions for water supply.

8.1.2 GCMs

Sixteen GCMs were coupled with the three emissions scenarios to simulate the global atmosphere and oceans and provide projections of specific climatological forcings (principally temperature and precipitation) during the period 1950 to 2099. Many of the GCMs were simulated multiple times for the same emission scenario due to differences in starting climate system state (initial oceanic and atmospheric conditions); thus, the number of available projections (112) is greater than simply the product of the number of GCMs and emission scenarios. Appendix B2 provides a summary of the GCMs, initial conditions, and emissions scenario combinations featured in the Study. Recent research (Pierce et al., 2009; Gleckler et al., 2008) has shown the importance of incorporating multiple climate projections (even when derived from the same GCM) and the superiority of the multi-model ensemble for a wide array of climate metrics. The subsequent results presented on future climate (primarily temperature and precipitation) and, indirectly, streamflow rely on the data generated by these GCMs.

8.1.3 Bias Correction and Spatial Downscaling

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

The purpose of bias correction was to adjust a given climate projection for inconsistencies between the simulated historical climate data and observed historical climate data. In the BCSD approach, GCM projections were bias corrected at a 2-degree resolution using a quantile mapping technique which corrects the simulated historical monthly temperature and precipitation projections to be consistent with the observed distributions at the same resolution. Following bias correction, the adjusted climate projection data were statistically consistent (monthly cumulative distribution functions were identical) with the observed climate data for the historical overlap period of 1950 to 1999. The bias correction quantile maps derived from the historical overlap period were then used to adjust the GCM projections for the future period. Note that this method assumes that the GCM biases have the same structure during the 20^{th} and 21^{st} Centuries' simulations.

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

8.1.4 Daily Weather Generation (Temporal Dissaggregation)

The resulting BCSD climate projections provided a representation of future monthly temperature and precipitation through 2099. However, to be useful for hydrologic modeling, this information was required on a daily temporal scale. The monthly downscaled data was temporally disaggregated to a daily temporal scale to create realistic weather patterns using the sampling methods described in Wood et al. (2002). To generate daily values, for each month in the simulation a month was randomly selected from the historic record for the same month (e.g., for the month of January, a January is selected from the 1950 to 1999 period). The daily precipitation and temperature data from the historic record were then adjusted (rescaled precipitation and shifted temperature) such that the monthly average matches the simulated monthly value. The same historic month was used throughout the domain to preserve plausible spatial structure to daily storms. The results of the temporal disaggregation were daily weather sequences that preserve the monthly values from the downscaled climate projections. Some uncertainties were introduced depending on the method employed to produce the daily data from the monthly climate values. A comparison of two available methods (Wood et al., 2002, and extension of Wood et al., 2002, described in Salathé, 2005) to generate daily weather patterns for the Study favored the use of the Salathé, 2005, method employed in the SECURE Report to produce the daily downscaled data. An additional description of the comparative analysis is presented in appendix B3.

8.1.5 Hydrologic Modeling

The daily weather sequences were used as input to the VIC hydrologic model to generate estimates of hydrologic fluxes and streamflow under various climate futures. For each of the 112 climate projections, the VIC hydrologic model produced a distinct trace of natural flows at each of the 29 natural flow locations.

Developed at the University of Washington, the VIC model is a semi-distributed, macro-scale hydrologic model that solves the water balance at each model grid cell. A VIC model of the Basin was previously developed by the University of Washington (Christensen and Lettenmaier, 2007), and was provided to Reclamation for the Study. The model has not been further calibrated or refined as part of the Study, but the model performance and bias correction has been evaluated and is discussed in the next section. A thorough description of the VIC model is provided in appendix B4.

Analysis shows (presented in appendix B4) that there are some biases in the VIC streamflows as driven by historical observed and downscaled climate model simulated historical meteorological forcings in comparison with the natural flows for the Basin for the overlapping period of 1950 to 1999. These biases are generally small for mainstem Colorado River locations, but can be large for smaller watersheds and in areas where the VIC model was not specifically calibrated. The mean annual flow bias for the Colorado River at Lees Ferry, Arizona, is positive 1.1 percent. Moving upstream to the three largest contributors to flow at Lees Ferry, the bias is negative 3 percent for the Green River near Green River, Utah, less than 1 percent for the Colorado River near Cisco, Utah, and negative 6 percent for the San Juan River near Bluff, Utah. The VIC model appears to have higher biases in the upper watersheds and lower biases farther downstream as more of the watershed contributes to the flow. In general, the upper Colorado River locations exhibited a positive bias, while the Green River and San Juan River locations exhibited a negative bias.

These biases are due to differences between the GCM-simulated historical climate and observed climate data, differences in hydrology model inputs and parameterization, and differences between the VIC-simulated hydrologic responses and observed watershed responses implied in the natural flows. The lack of calibration of the VIC model for lower order streams within the Basin is believed to be a significant source of the bias at these scales.

A streamflow bias correction method was developed and applied to the “raw” VIC-simulated flows to account for any systematic bias in the hydrology model and/or climate data sets. The method corrected for monthly and annual biases, while ensuring that the corrected flows maintained the system and local mass balance. The raw VIC-simulated streamflows for both the historical and future periods were first adjusted for biases before incorporating into the CRSS modeling. The streamflow bias correction step was an important component for the use of climate-driven hydrologic modeling and results in subsequent systems modeling. Without this step, the VIC-simulated historical flow biases would be carried forward into future assessments and the potential existed for misattribution of some streamflow changes to changes in climate, while these may be partially associated with model/data bias. Details on the methods used to correct for biases are included in appendix B4.

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

Additional detail on VIC and its application for the Study can be found in appendix B4.

8.1.6 Systems Modeling

A total of 112 realizations at the 29 natural flow locations were taken from the VIC model simulations and subsequently corrected for streamflow biases. Differing from the three other future water supply scenarios, which do not address changes in climate, each Downscaled GCM Projection hydrologic sequence of streamflow exhibits a long-term future trend and increased variability beyond what occurred historically. For the Study, no differentiation was applied for each of the sequences, based on emission scenario or historical GCM skill. In essence, each of the 112 sequences was treated as equally likely when applied in CRSS in later phases of the Study. Included in this report is an evaluation of the relative sensitivity of streamflows to emission scenarios. From a mechanical standpoint, the Downscaled GCM Projected scenario was implemented as 112 distinct projections of the future, each starting in the year aligned with the Study period start year of 2011.

8.2 Uncertainty

The process outlined above and shown graphically in figure B-36, in which climate projections are used to generate projections of future streamflow, contains a number of areas of uncertainty. Each step in the process contains uncertainty, and it is important to recognize these in the interpretation of results. First, emission scenarios describing the global emissions of GHGs over the century were used as the primary input to GCMs. The SRES emission scenarios were used to project a range of future global development pathways. Each emission scenario was considered plausible, but the fact that the range may not be sufficiently broad cannot be ruled out. In addition, the climate system responds to a number of factors that contribute to radiative forcings affecting the warming of the earth’s surface. Factors such as aerosols, solar activity, surface albedo, and variations in the earth’s orbit, all influence the earth’s energy balance. These mechanisms are included in the climate models to the degree they are understood and can be projected into the future, but represent an inherent uncertainty in attempting to simulate the global climate system on decadal and century scales. Anthropogenic carbon dioxide emissions, which are directly represented in the emission scenarios, are believed to represent the largest component of the estimated radiative forcing (IPCC, 2007).

Second, GCMs are used to simulate global climate patterns resulting from atmospheric forcings and feedbacks throughout the land, ocean, and atmosphere interactions. The GCMs were applied at relatively coarse scales (~150- to 200-km resolution) in relation to what is required for watershed assessments, and therefore are not likely to capture important regional phenomena. Because of the atmospheric lag from GHG emissions, much of the uncertainty in climate projections through mid-century is associated with the structure and application of the many different GCMs themselves, rather than the emission scenarios driving them. The GCM results were necessarily bias corrected and spatially downscaled to be useful at the watershed scale. These bias correction and downscaling processes, while necessary, removed some of the physical linkages from the climate projections and introduced an aspect of further uncertainty. High-resolution regional climate modeling may help resolve some of the scale mismatch (both spatially and temporally) in the future, but the availability of these simulations over a broad ensemble of models and emission scenarios is limited. The statistical downscaling method employed in the Study preserves monthly observed precipitation and temperature statistics for the overlapping period at the 2-degree spatial scale. However, the statistics at finer spatial scales (i.e., 1/8th-degree scale) or longer temporal scales (seasonal, annual, and longer scales) are not necessarily preserved. Analysis included in appendix B3 provides further information on this topic.

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

In addition, the VIC model, as described in this report, has been adopted without re-calibration. Results appear reasonable at the larger watershed scale, but there is observed bias in particular watersheds and at the sub-watershed scale. A bias correction method has been applied to compensate for some of the biases, but in doing so it necessarily introduces assumptions on the linkages between past and future climates that are not yet known.

8.3 Results

The results of the 112 future climate projections are presented in this section for climate, hydrologic processes, and streamflow. Climate teleconnections are discussed primarily in a qualitative manner due to the broad uncertainty in projecting future states of coupled ocean-atmosphere conditions. For climate, results are presented in terms of annual precipitation and temperature trends, followed by an analysis of seasonal trends. For hydrologic processes, results are presented for ET, snowpack, soil moisture, and runoff. Both annual and seasonal analyses are presented. The last section of the results focuses on projected changes in streamflow, both annual and seasonal, and predominately at the Colorado River at Lees Ferry, Arizona location.

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

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

Under the scenario planning approach employed in the Study, each future climate projection was viewed as a plausible future. The probability or likelihood of each future projection is unknown, hence summary statistics of the resulting projections such as mean or median of the ensemble projection is not the most likely future, but simply the central tendency of the ensemble. For the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios summary statistics are grounded by a stationary hydroclimate assumption. Given the increasing debate concerning the validity of a stationary hydroclimate assumption, it is tenuous to assert that the past record is predictive of future conditions. Thus, while summary statistics such as mean and median are used in part to present these data, it is important to consider the full range of outcomes, which are also provided throughout these results.

In the case of the Downscaled GCM Projected scenario, this consideration is further complicated by the ensemble of results. Each of these traces is a unique combination of initial conditions, GCM choice, and future emission scenario. The resulting streamflows are all considered plausible futures. However, summary statistics can be computed by various approaches, which influence the outcome of these values. Thus, understanding the full range of results is even more paramount in this supply scenario. Recent literature on the topic has found that an ensemble of results with multiple realizations from a single GCM can inadvertently bias the ensemble statistics favoring the GCM with multiple realizations. Hence, in some cases it may be prudent to combine realizations from each GCM such that each contributes equally to the ensemble and associated statistics. The alternate perspective suggests that with more runs from a particular GCM, there is greater confidence and understanding of the GCM’s tendencies. This is desirable and might merit greater weight than a GCM with only one realization. The latter introduces sizable uncertainty to the ensemble as it is unknown if additional realizations from the GCM with a single realization would yield similar results or vary widely. In practice, the most prudent approach is a case by case consideration of these and other methods to determine the most appropriate path forward. In the Study, the results were found to be insensitive to the method by which summary statistics were computed (ensemble mean streamflow projections were within 1 percent of each other under both approaches). Results presented throughout the following sections weight all GCM realizations equally simply describing summary statistics based on the 112 available projections. Acknowledging that a summary statistic alone cannot capture the complexity of these results, ranges, percentiles and other distributional measures are also provided.

8.3.1 Climate

Climate projections from the 112-projection ensemble indicate a strong continued warming throughout the Basin. Figure B-37 shows the Basin average temperature and precipitation projections for 1950 to 2099 (the length of the GCM projection period) in relation to the 1950 to 2005 (the length of the observed climate period) historical observed climate. The projection ensemble indicates substantial warming, with a median increase in annual temperature of about

1.3 ºC by 2025, 2.4 ºC by 2055, and 3.3 ºC by 2080. All projections are consistent in the direction of the temperature change, but vary in terms of climate sensitivity. Annual precipitation trends are not apparent in this Basin-wide analysis. Roughly half of the projections indicate a wetter future, while the other half indicate drier conditions. The uncertainty in future annual precipitation appears to be increasing with time, while the median of the projections is relatively unchanged.

Figure B-38 presents the change in mean annual temperature (absolute change) and precipitation (percent change) for three future periods: 2011 to 2040 (2025), 2041 to 2070 (2055), and 2066 to 2095 (2080), relative to the 30-year historical period 1971 to 2000 (1985). For most of the Basin, temperature increases are within 1.0 °C to 1.5 °C, 2.0 °C to 2.5 °C, and 3.0 °C to 4.0 °C for 2025, 2055, and 2080, respectively. The Upper Basin is projected to warm more than the Lower Basin. Projected precipitation changes are relatively modest in 2025. However, by the 2055 and 2080 periods, precipitation decreases by up to 10 percent in much of Lower Basin. In contrast, precipitation increases by up to 10 percent in the Upper Basin at higher elevation and toward the north (Green River Basin).

Maps of seasonal changes in temperature and precipitation for the three future 30-year periods are included in appendix B6 and are summarized here.

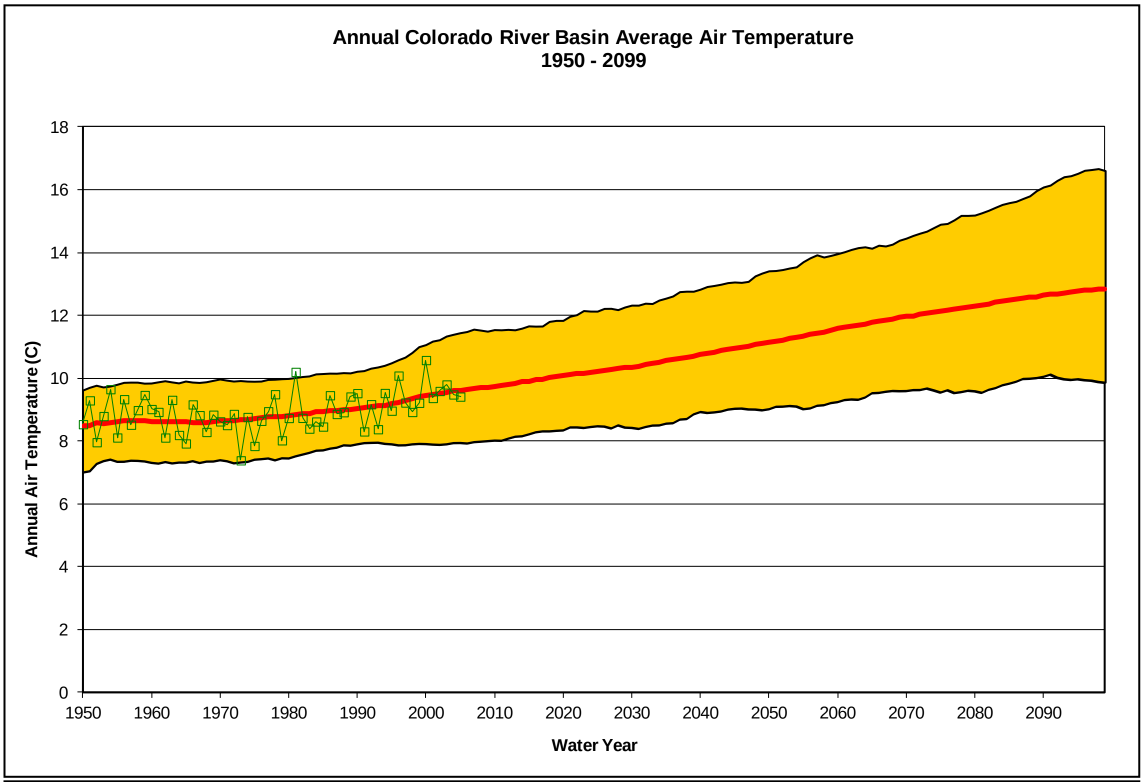
The seasonal analysis shows that 2055 projected seasonal temperature changes exhibit minimal geographic variation in the fall. Winter and summer temperatures in the Upper Basin increase slightly more than those in the Lower Basin. Projected temperature increases are lowest in winter, ranging from 1.5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

The 2055 change in projected mean winter precipitation is highly varied throughout the Basin, with values in the Lower Basin decreasing from 0 to 15 percent and the values in the Upper Basin increasing from 0 to 15 percent. However, it should be noted that on an absolute basis, the Upper Basin receives considerably more rainfall than the Lower Basin, such that a 15 percent change is substantially more total precipitation in that region. During spring, precipitation is projected to decrease throughout the Basin. The most severe reductions (on a percentage basis) occur in the southwestern region, where the decline is up to 30 percent. Summer is the only season in which projected precipitation shows a decrease in the Upper Basin and an increase or no change in the Lower Basin. Trends in fall precipitation closely resemble those of the winter season, but the projected percent changes for fall are lower in magnitude.

Figure B-39 summarizes projected changes in climate conditions on a watershed basis, as indicated by the 112-projection ensemble for the three future 30-year periods. Each point represents a single watershed (one for each contributing area). The location of a point in the figure is determined by the mean projected change in temperature between the future periods and the simulated historical period 1971 to 2000, and the mean projected change in precipitation between the future periods relative to the simulated historical period. Change in temperature is measured in ºC, while change in precipitation is measured as a percentage.

FIGURE B-37
Historical (line series with markers) and Projected Annual Average Temperature (top) and Projected Annual Total Precipitation (bottom) Smoothed as a 10-year Mean

Shading represents a range of projections and the solid line represents a median of projections.



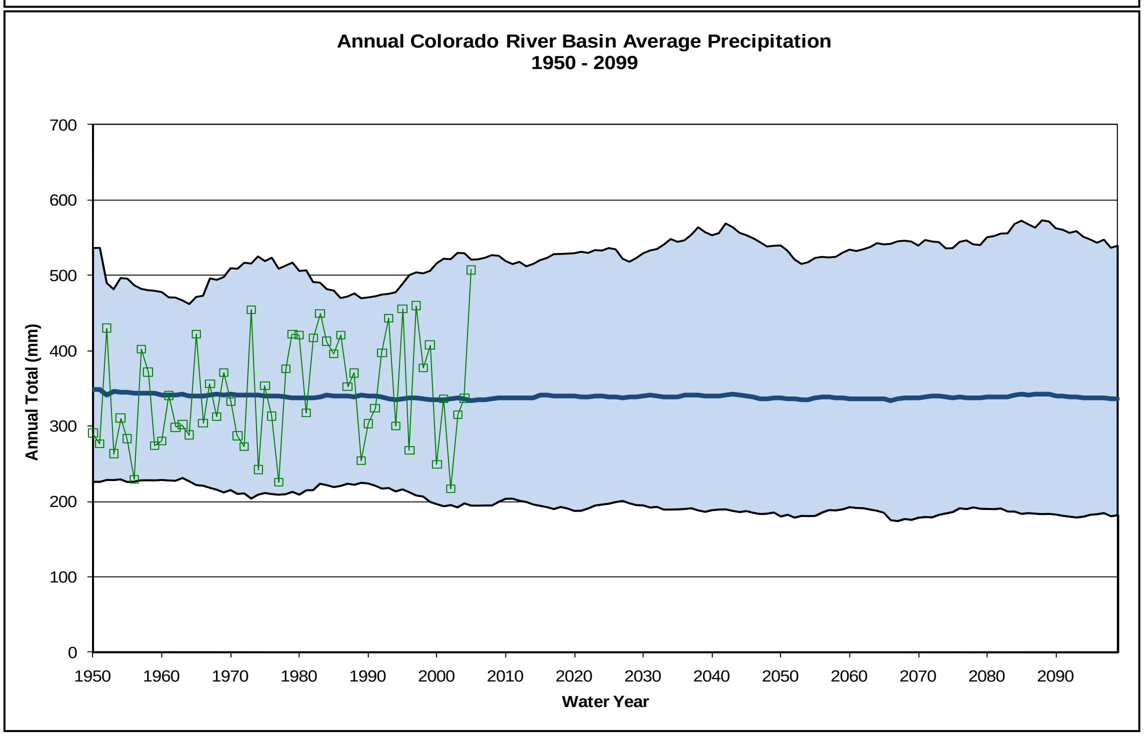


FIGURE B-38
Mean Projected Change in Annual Temperature and Precipitation
2025 (2011–2040) versus 1985 (1971–2000), 2055 (2041–2070) versus 1985 (1971–2000), and 2080 (2066–2095) versus 1985 (1971–2000).

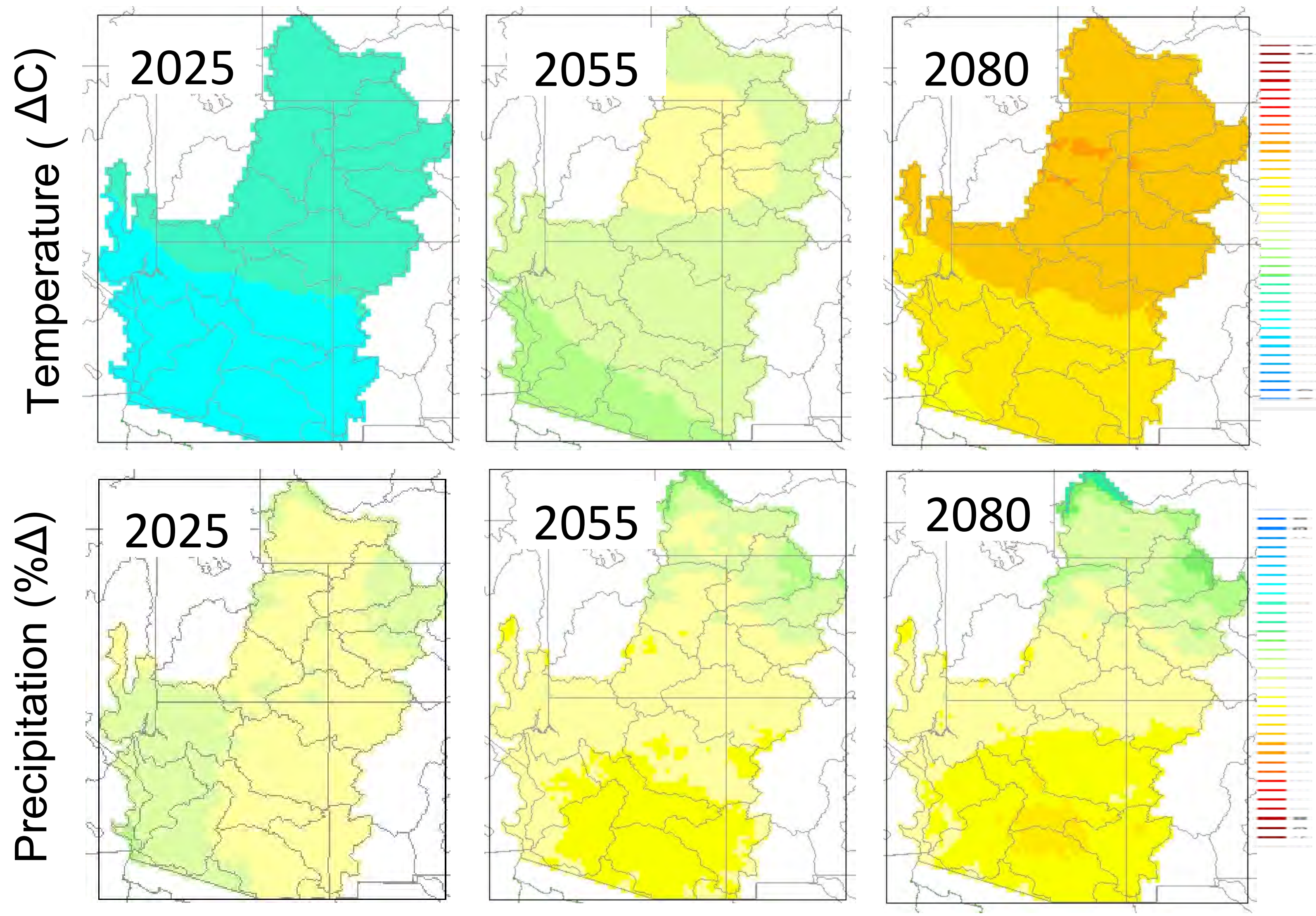
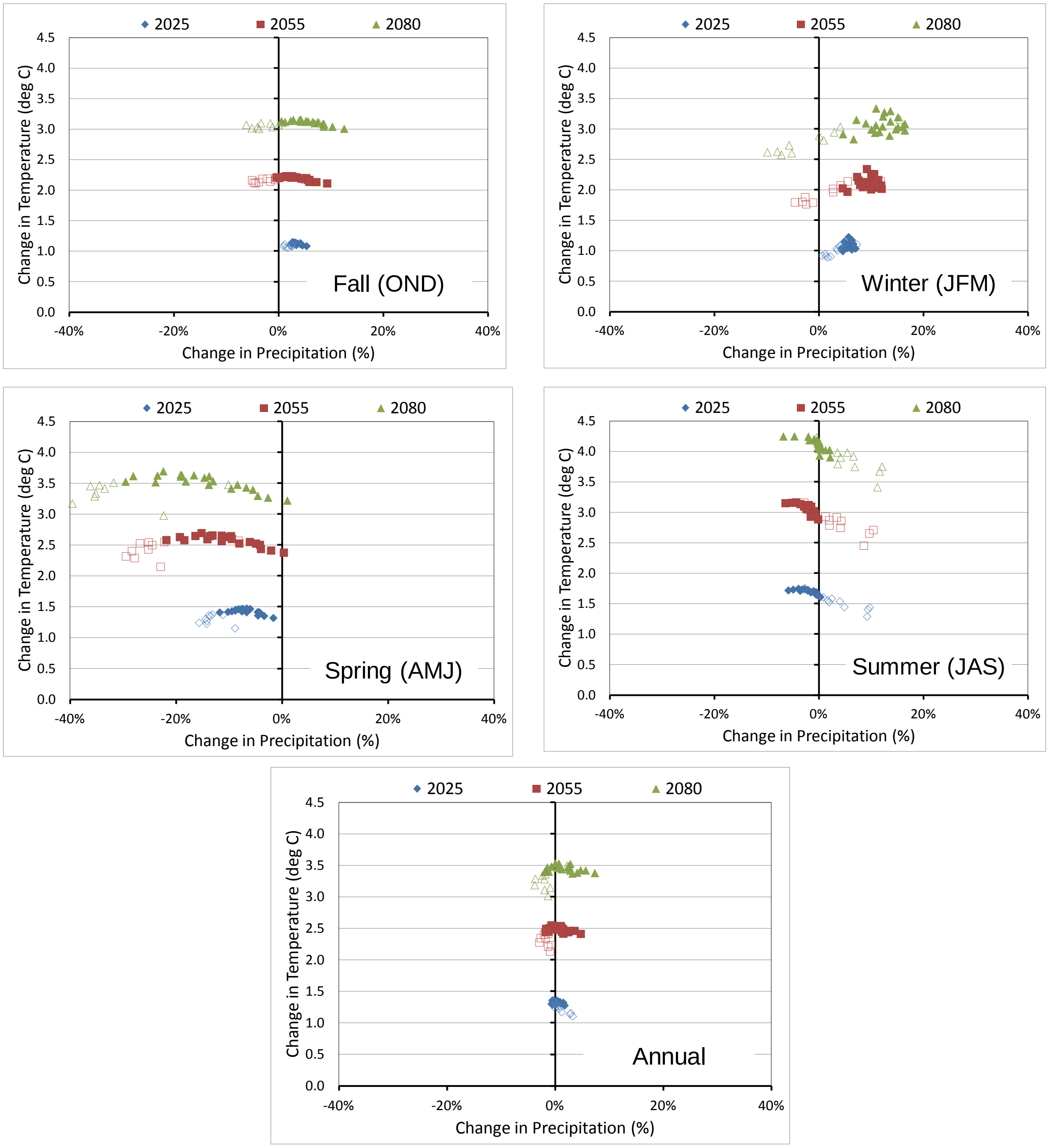


FIGURE B-39
Projected Changes in Mean Seasonal and Annual Temperature and Precipitation for the Colorado River Basin
Periods are 2025 (2011–2040); 2055 (2041–2070); and 2080 (2066–2095), compared to the 1985 (1971–2000) historical period (hollow symbols represent Lower Basin locations, while solid symbols indicate Upper Basin locations).



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

Projected changes in seasonal precipitation vary widely across watersheds and seasons. In general, relative precipitation variability increases with time. On an annual basis, projected precipitation through 2080 is generally within 5 percent of historical precipitation, with half of the Basin's watersheds exhibiting positive change and half exhibiting negative change. The most significant and monotonic change in precipitation occurs in spring, during which all watersheds show a decrease in precipitation for each of the future time periods. By 2080, the decrease in spring precipitation ranges from 0 to 40 percent, with the values well distributed within the range. During fall and winter, small increases (less than 10 percent) are projected for 2025, but bimodal patterns of increases in the Upper Basin (about 20 percent for winter in 2080) and decreases or neutral changes in the Lower Basin (about 10 percent for winter in 2080) begin to appear in the 2055 and 2080 time periods. Summer is the only season in which the bimodal pattern is reversed with decreases in precipitation projected in the Upper Basin and increases in the Lower Basin (see appendix B6 for projected seasonal precipitation maps). The summer pattern is likely due to a more active monsoon and increased moisture flow from the Gulf of California during this season simulated in the GCMs, although the summer precipitation associated with the monsoon is poorly simulated in most climate models (Lin et al. 2008; Gutzler et al. 2005).

8.3.2 Summary of Changes in Climate

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

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

8.3.3 Hydrologic Processes

Figures B-40 and B-41 present grid cell-based VIC model output via Basin-wide spatial plots for ET, runoff, soil moisture, and SWE. For each future time period and for each parameter, the mean projected annual changes are presented. Projected seasonal changes for these parameters can be found in appendix B6.

Figure B-40 shows the percent change in mean annual ET and mean annual runoff. ET is projected to increase in most high elevation and northerly areas of the Upper Basin and is strongly related to the availability of soil moisture. In the Lower Basin, where decreased precipitation is projected (and subsequently reduced soil moisture), ET is projected to decrease substantially, particularly in the 2055 and 2080 periods. Runoff is projected to decrease substantially (up to 30 percent) across large areas of the Basin, with greatest reductions in the south and at high elevation. Elsewhere, projected decreases are generally within 15 percent of the historical period through 2080. Runoff is projected to increase for small areas in the northeastern portion of the Basin (Green River Basin primarily). The increases in the northern portion of the Basin are an important finding and contribute significantly to mitigate reduced runoff trends for much of the rest of the Basin.

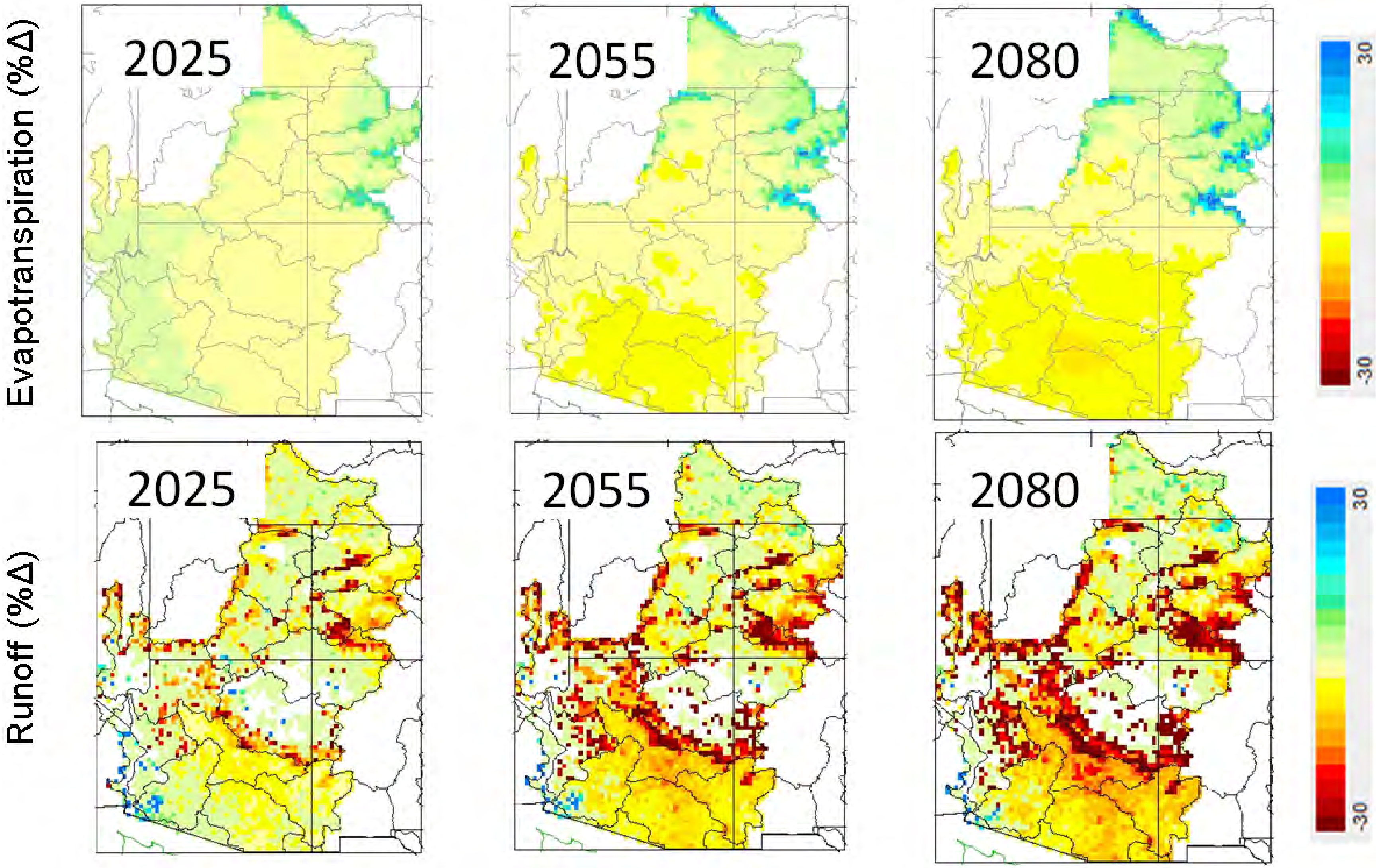
Figure B-41 shows the mean percent change in April 1 SWE and July 1 soil moisture. With few exceptions, April SWE is projected to decline by up to 30 percent throughout the Basin by 2025 as more precipitation falls as rain and as warmer conditions lead to earlier snowmelt. This process becomes more pronounced in the 2055 and 2080 periods. July 1 soil moisture is projected to decrease by 5 to 10 percent throughout the Basin for the three future time periods. The loss of soil moisture is primarily the result of the greater moisture availability for ET earlier in the year (more rain less snow and earlier melt of snowpack) in the higher elevation Upper Basin and reduced overall precipitation in the Lower Basin. The most substantial decline occurs in the northeast portion of the Basin.

Maps of seasonal changes in ET, runoff, soil moisture, and SWE for the three future 30-year periods are included in appendix B6 and are summarized here.

Projected 2055 changes in ET vary substantially throughout the Basin. In general, ET is projected to increase during fall and winter, but decrease during summer for the majority of the Basin. Projected ET changes exhibit considerable geographic variability and range in magnitude during spring, when portions of the Upper Basin have ET increases of up to 30 percent and portions of the Lower Basin have ET decreases of up to 30 percent. Both phenomena are related to soil moisture availability. Increases in Upper Basin ET are due to greater soil moisture availability, while Lower Basin decreases are due to reduced available soil moisture. During summer, projected 2055 changes in ET range from -5 to -10 percent in most locations.

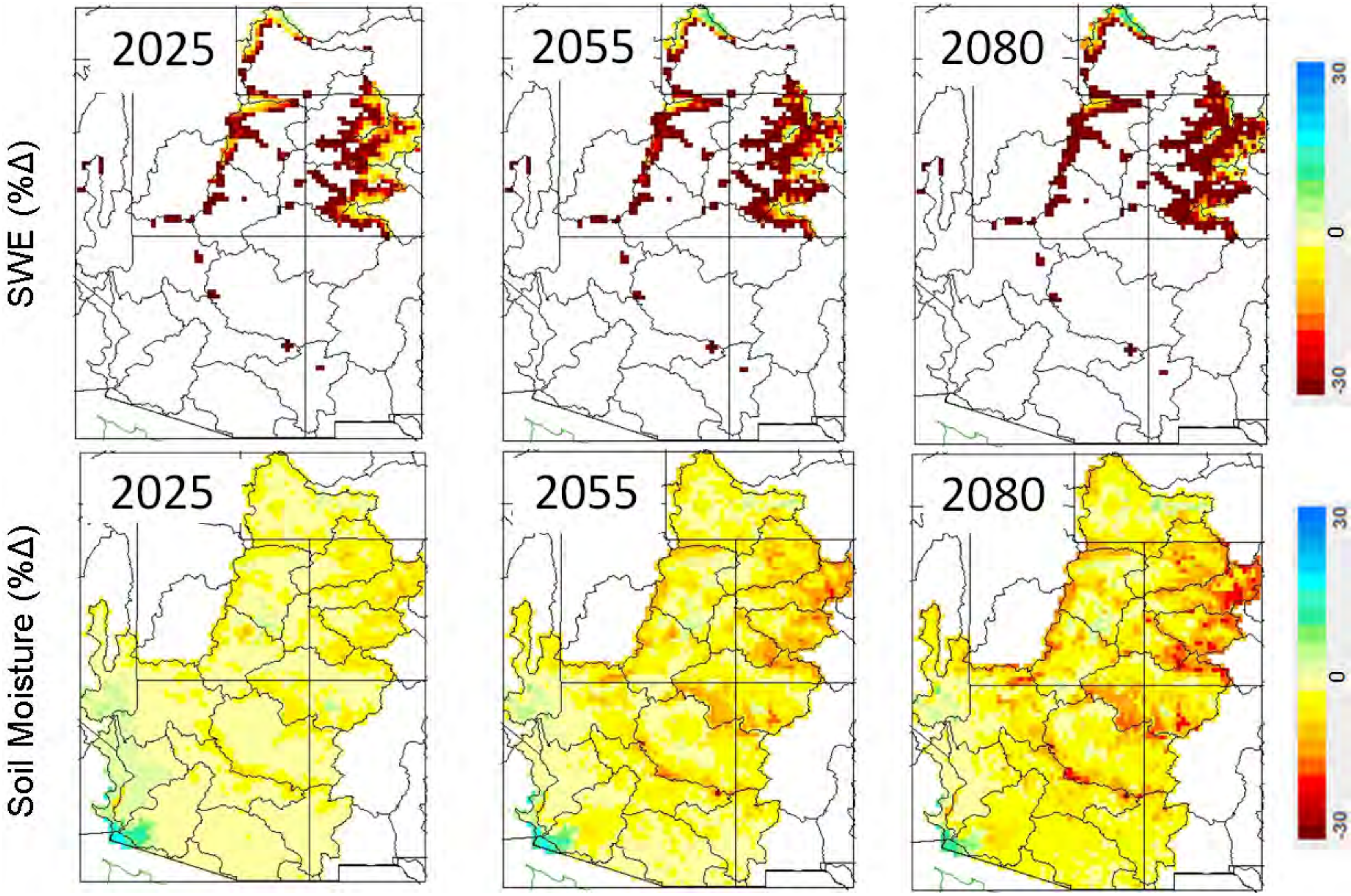
Projected 2055 changes in runoff also vary substantially throughout the Basin. In most seasons, runoff declines throughout the Basin. However, increases are projected for portions of the Upper Basin in fall and winter, and for the extreme southwestern portion of the Basin for all seasons. The projected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

FIGURE B-40
Mean Projected Percent Change in Annual ET and Median Projected Percent Change in Runoff[1]
2025 (2011–2040) versus 1985 (1971–2000), 2055 (2041–2070) versus 1985 (1971–2000), and 2080 (2066–2095) versus 1985 (1971–2000).



[1] Median is used for runoff percent change, rather than mean because regions of extreme low historical precipitation may show disproportionately high percentage changes.

FIGURE B-41
Mean Projected Percent Change in April 1 SWE and July 1 Soil Moisture
2025 (2011–2040) versus 1985 (1971–2000); 2055 (2041–2070) versus 1985 (1971–2000); and 2080 (2066–2095) versus 1985 (1971–2000).



The results of the watershed-based statistical analysis of VIC model output (climatological and hydrologic parameters) are presented for two representative Basin watersheds. The selected watersheds are those immediately upstream of the Colorado River at Glenwood Springs, Colorado, and the Colorado River at Hoover Dam. These select watersheds represent a high elevation headwaters region in the Upper Basin and a lower elevation, warmer region in the Lower Basin. Additional locations representing a more-robust cross-section of the Basin are included in appendix B6.

Figures B-42 and B-43 each present the changes in six hydrologic parameters (precipitation, temperature, ET, runoff, SWE, and soil moisture) from the 30-year historical period (1971 to 2000) to three future 30-year periods: 2011 to 2040 (2025); 2041 to 2070 (2055); and 2066 to 2095 (2080). Figure B-42 presents these hydrologic parameter changes for the Colorado River at Glenwood Springs, Colorado. The results for this watershed are representative of those for other watersheds in the high elevation Upper Basin:

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

Figure B-43 presents these plots for the Colorado River at Hoover Dam. The results for this watershed are representative of those for other watersheds in the Lower Basin. Due to the limited snowpack in the Lower Basin and its resulting limited role in the hydrologic processes of this region, the SWE results for the Lower Basin are not considered in these plots. Relative to the

FIGURE B-42
Projected Change in Mean Monthly Climatological and Hydrologic Parameters: 01-Colorado River at Glenwood Springs, Colorado (Upper Basin)

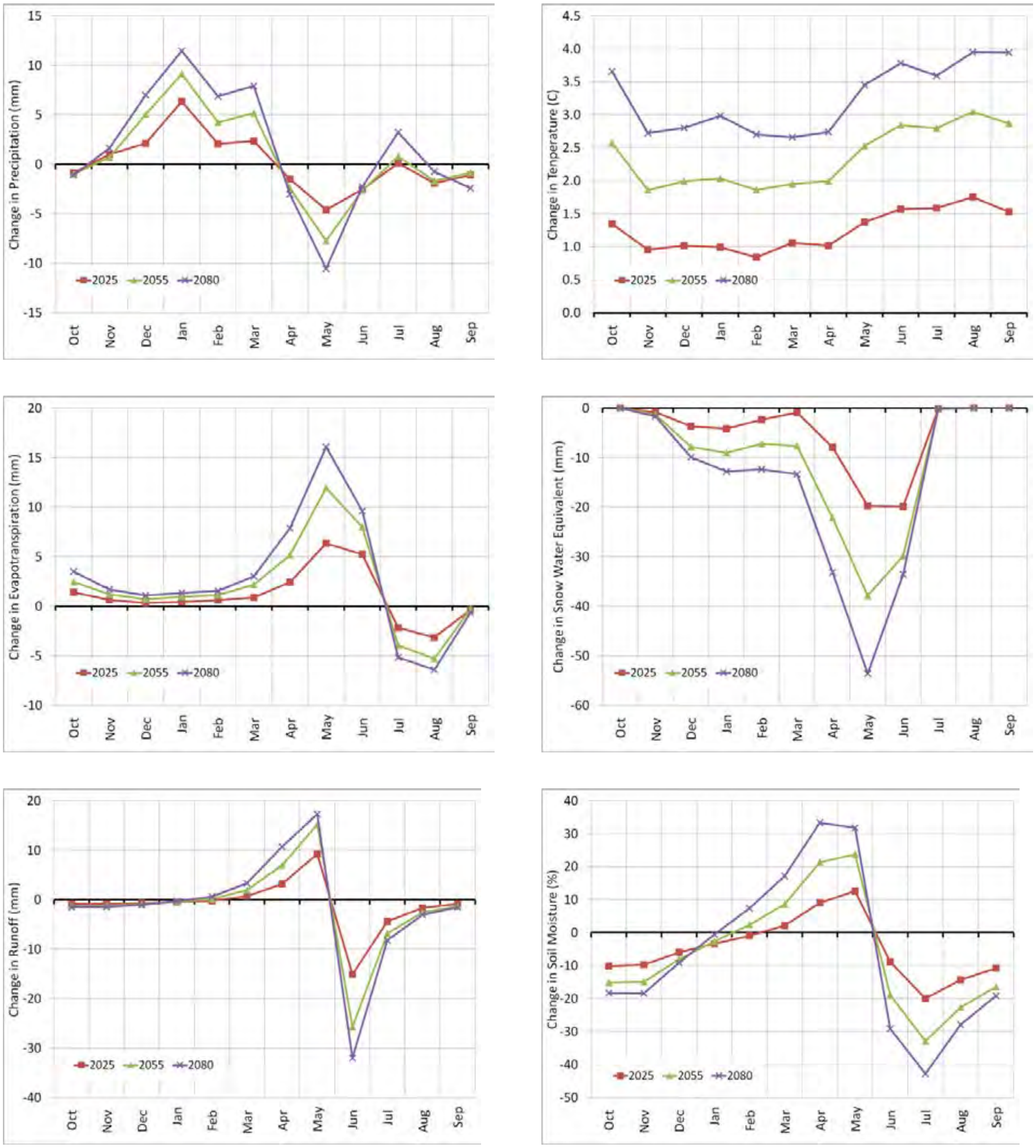
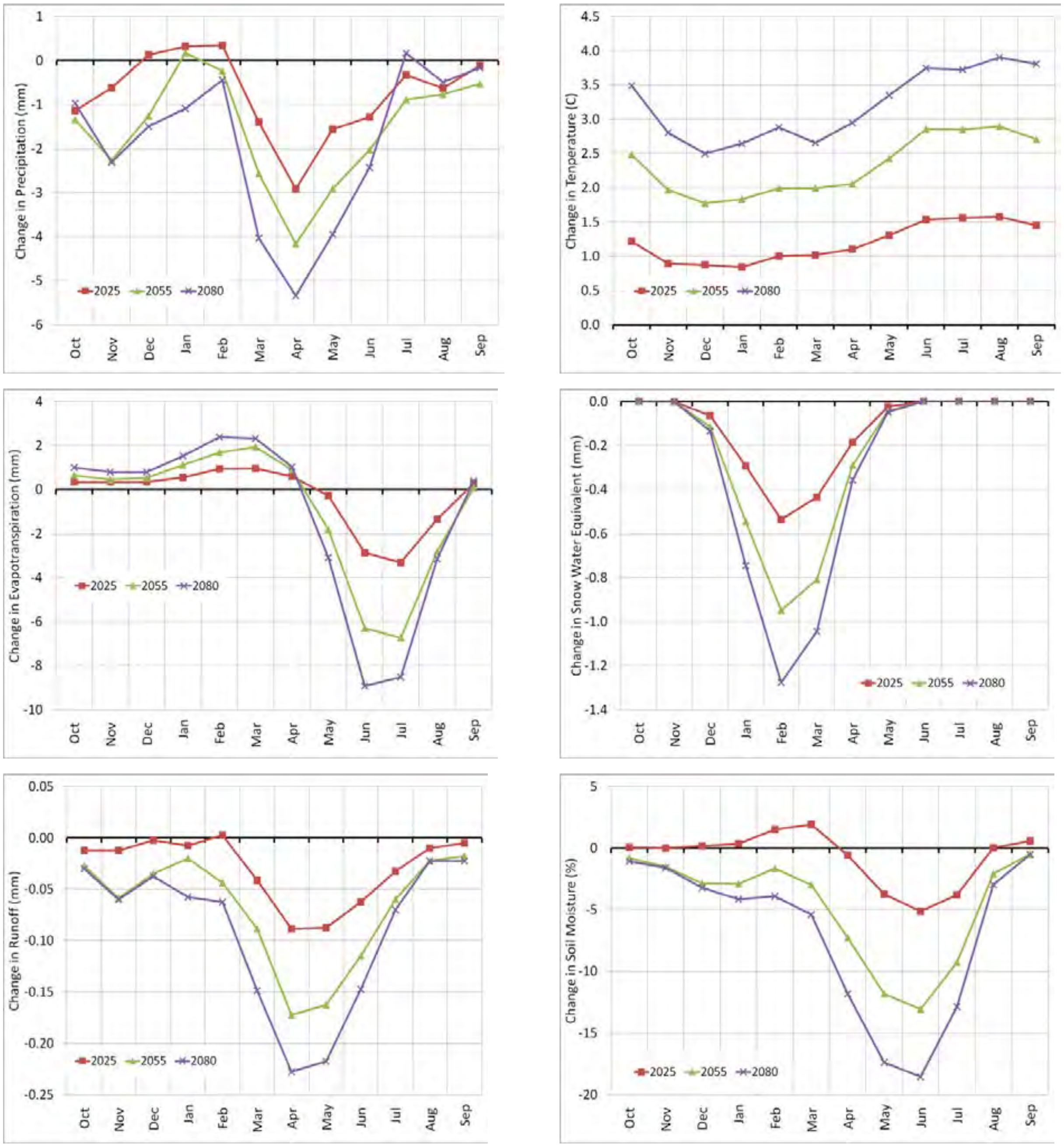


FIGURE B-43
Projected Change in Mean Monthly Climatological and Hydrologic Parameters: 25-Colorado River at Hoover Dam



Upper Basin, the changes projected for the Lower Basin are smaller in magnitude on an absolute scale (e.g., change in mm rather than change in percentage):

- Precipitation: In the Lower Basin, precipitation is projected to decrease during half of the year, with spring exhibiting the most notable decline.
- Temperature: Monthly temperature increases are projected throughout the year ranging from 1.5 °C by 2025 to 4.0 °C by 2080.

- Evapotranspiration: ET is noticeably reduced in late spring and early summer, though modest increases are projected for winter. The marked reductions in late spring and early summer are likely due to the reductions in precipitation, runoff, and soil moisture that occur during these times.
- Runoff: Runoff is reduced during all seasons at this location and is more pronounced in the 2055 and 2080 time periods. Reductions result from the compounding effects of decreased precipitation and increased winter and early spring ET. It should be noted that runoff in this watershed (and similar watersheds in the Lower Basin) is very small and contributes little to the overall flow in the Colorado River. Runoff is usually less than 5 to 10 percent of the precipitation in this region.
- Soil Moisture: Soil moisture is projected to be lower year round, with the largest reductions occurring in the spring.

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

8.3.4 Summary of Changes in Hydrologic Processes

- PET generally increases with warmer conditions and suggests a theoretical increase in ET demand. Actual ET, which is limited by soil moisture availability, is projected to increase across the Basin during seasons of highest available soil moisture. ET increases are projected in the Upper Basin (at lower elevations) and the Lower Basin in fall and winter as snowpack is not significant and warmer temperatures exist. Substantial ET decreases in the Upper and Lower Basin are projected in summer as soil moisture is depleted earlier than under historical conditions. During spring, peak increases in ET are projected in the Upper Basin (at higher elevations) as higher winter precipitation and earlier snowmelt allow a higher percentage of PET to be satisfied. Conversely, in the Lower Basin, the largest decreases are projected during the spring as precipitation, runoff, and soil moisture are reduced during this time. ET changes described here are from natural watershed and non-irrigated areas. ET effects on irrigated areas and water demand are discussed in *Technical Report C – Water Demand Assessment*.
- Snowpack is projected to decrease as more precipitation falls as rain rather than snow and warmer temperatures cause an earlier melt. Decreases in snowpack in the fall and early winter are expected in areas where precipitation is not changed or is increased, and is caused by a greater liquid form of precipitation due to warming. Substantial decreases in spring snowpack are expected and projected to be widespread, due to earlier melt or sublimation of snowpack.
- Soil moisture represents a significant portion of the seasonal watershed storage and buffers monthly changes in water availability and consumptive use. The interplay among precipitation, snowpack, ET, and runoff causes changes in soil moisture conditions. In general, soil moisture is depleted earlier in the year, and deficits persist longer into the late fall and early winter compared to historical conditions. In regions with overlying snowpack, earlier melt implies earlier contribution to soil moisture storage and an earlier opportunity for ET to consumptively use this stored water. In all regions, there is projected to be increased

PET due to warming. However, actual ET is governed by water availability; and when such soil moisture storage is depleted actual ET is curtailed. Reductions in soil moisture at the beginning of summer (approximated as July 1) are modest but consistent throughout the Basin. Larger reductions are projected in the higher elevation portions of the Basin where moisture persists longer. Overall, the watershed enters the winter season with larger soil moisture deficits and greater opportunity to store and consume winter precipitation.

- Runoff (both direct and baseflow), the balance of hydrologic processes affecting the supply and demand at the local grid-scale, is spatially diverse, but is generally projected to decrease, except in the northern Rockies. As with precipitation, runoff is projected to increase significantly in the higher elevation Upper Basin during winter, but exhibits decreases during spring and summer. Increases in runoff in the summer across the southwestern portion of the Basin are consistent with higher precipitation rates, possibly associated with a more active monsoon. However, the increases from an absolute change perspective are small (generally less than 5 mm [0.15 inch] per year) and do not contribute to substantial net supply to the Colorado River. Due to the minimal amount of annual rainfall in this region, however, caution should be taken in interpreting a percentage increase (a small increase from near zero is a large percentage increase).

8.3.5 Climate Teleconnections

Climate change projections of ENSO characteristics for the balance of this century are model-dependent and inconclusive. Not all the GCMs used in the Study simulate the dynamics of ENSO and other longer-term indices with fidelity. AchutaRao and Sperber (2002) evaluated ENSO simulations using 80-year control runs from 17 GCMs that participated in the CMIP3. They found that only a subset of the GCMs produce realistic amplitudes of NINO3 (index of the sea surface temperatures in the Pacific Ocean) and SOI, but ENSO often tends to occur at higher than observed frequency. In their recent study (AchutaRao and Sperber, 2006), though, they find the next generation GCMs that participated in the IPCC AR4 tend to be more realistic in representing the frequency with which ENSO occurs. The GCMs are better at locating enhanced temperature variability over the eastern Pacific Ocean. They suggest multi-century integrations of GCMs may be required to statistically assess model improvement of ENSO.

ENSO has an important role in western U.S. climate. Whether the frequency and characteristics of ENSO will be changed in a changing climate has strong practical importance. A few of the recent studies analyzed GCM simulations to address these questions (Yeh et al. 2009; Collins et al., 2010). However, there is no common consensus yet in the scientific community. Collins et al. (2010) argue that despite considerable progress in the understanding of the impact of climate change on many of the processes that contribute to El Niño variability, it is not yet possible to say whether ENSO activity will be enhanced or damped, or if the frequency of events will change. Yeh and Kirtman (2007) investigate two coupled GCMs—the Meteorological Research Institute’s model, and the Geophysical Fluid Dynamics Laboratory’s model—to analyze projected ENSO amplitude changes using a four times carbon dioxide emission scenario. They determine that despite the large changes in the tropical Pacific mean state, the changes in ENSO amplitude are highly model-dependent. Results suggest that the understanding of changes in ENSO statistics among various climate change projections is highly dependent on whether the model ENSO is in the linear or nonlinear regime. ENSO and PDO provide only limited skill in determining basin precipitation; thus, even improved simulation results for these indices may be of limited value in making assessments of future supply conditions. Further research is needed to investigate the teleconnections and the direction of these teleconnections in the future.

8.3.6 Streamflow

Natural streamflows were simulated at the 29 flow locations for each of the 112 climate projections. Figure B-44 displays all of the individual 112 sequences in the Downscaled GCM Projected scenario. The sequence bolded in figure B-44 also appears in figure B-45, which is a representative trace of the 112 sequences. In figure B-45, the mean annual flow of the 112 sequences at this location declines substantially over time due to changes in hydrologic processes. Mean annual flows for Colorado River at Lees Ferry, Arizona, for the 50-year period of the Study (2011 to 2060) are approximately 13.7 maf. This represents a reduction in streamflow of approximately 6 percent compared to the period 1950 to 1999 (14.6 maf), or approximately 9 percent compared to the long-term period 1906 to 2007 (15.0 maf). It should be noted that the median of the projections is nearly 1.0 maf lower (annual flow of around 12.7 maf) than the mean, indicating that the projection ensemble exhibits a strong drying trend but that some wetter projections are compensating in the mean statistic. A few projections (less than 10 percent) show considerably more annual variability than the observed record. Although simulated future minimum flows are similar to those in the observed record, the maximum annual flows are significantly higher.

Finally, figure B-46 shows the range of Colorado River flow projections under the Downscaled GCM Projected scenario as compared to the historical observed flows. Observed natural flows span from 1906 to 2007 while the projections begin in 1950 and extend through 2099. During the overlapping period of 1950 to 2007, the projection reflects the range of natural flows from the observed record. Interestingly, the projection ensemble indicates a declining trend starting in the 1990s and a significant expansion in variability starting in the late 2000s. A number of sequences in the Downscaled GCM Projected scenario exhibit occasional annual runoff conditions that far exceed the maximum in the observed or paleo records. Although it is possible that future climate will expand the magnitude and frequency of extreme events, it is also possible that some projections are simply extreme outliers from the ensemble. As shown in figure B-46, 5 to 10 percent of the projections show annual flows in excess of the maximum observed natural flow of 25 maf for any given year.

To better understand the issue of simulated extreme high flows and to determine whether specific GCMs or emission scenarios were driving this result, further analysis was conducted. For each downscaled climate projection, the cumulative difference from the simulated maximum flow to the maximum observed annual value of 25 maf over the study period 2011 to 2060 was computed. In addition, the total number of years in which the simulated flow exceeded 25 maf was counted for the 112 VIC model simulations. The results of this analysis are shown in figure B-47. Each of the 112 projections are listed and colored by the emission scenario (blue for A1B, red for A2, and green for B1). The corresponding dot represents the number of years in which that projection had simulated flows greater than 25 maf. The bar represents the cumulative flow above 25 maf. More than half of all GCM projections produced at least one event greater than 25 maf and these occurred regardless of emission scenario. None of the projections had more than 4 years in which they exceeded 25 maf. In addition, the GCMs with the largest deviations under one emission scenario produced fewer or no deviations under another emission scenario.

FIGURE B-44
Colorado River at Lees Ferry, Arizona Natural Flow for 112 Sequences for the Downscaled GCM Projected Scenario
The bolded line indicates a representative trace.

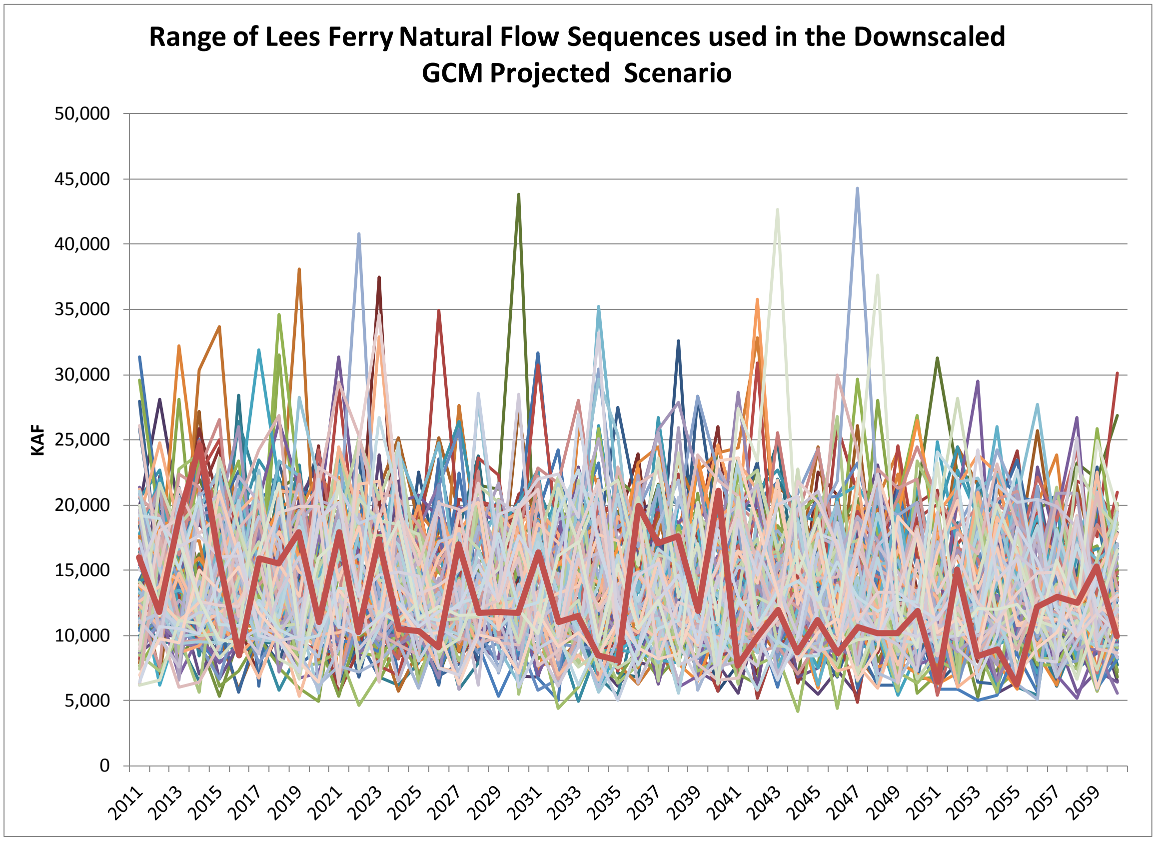


FIGURE B-45
Colorado River at Lees Ferry, Arizona Natural Flow Statistics for the Downscaled GCM Projected Scenario
Median (line), 25th–75th percentile band (dark shading), 10th–90th percentile band (light shading), max/min (whiskers), and 1906–2007 observed min and max (dashed lines). The red bolded line indicates a representative trace.

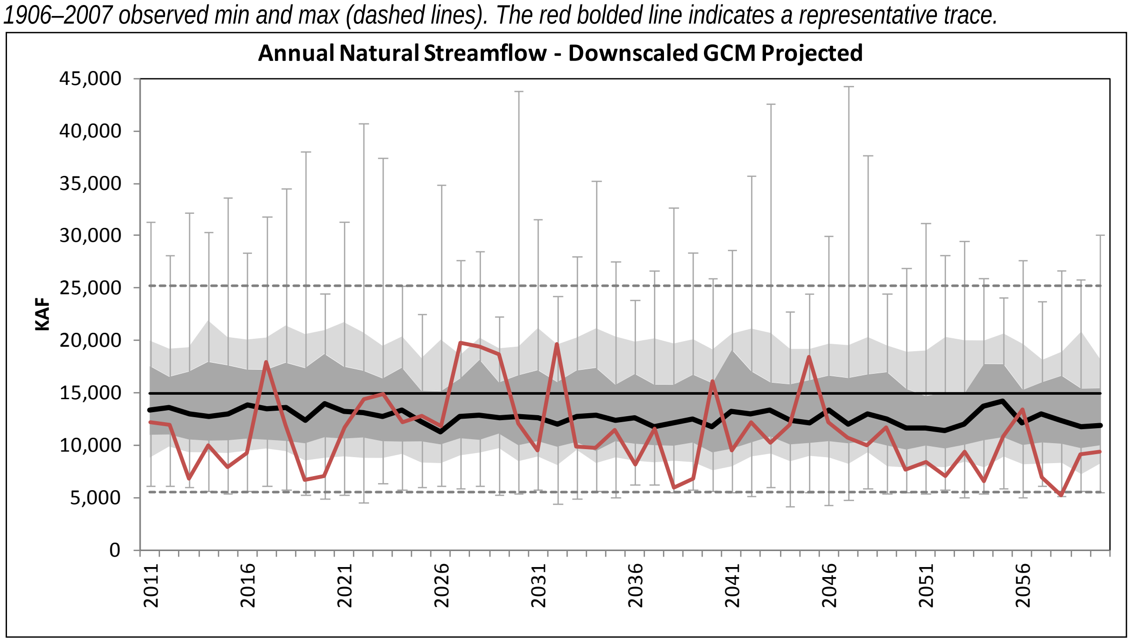


FIGURE B-46
Colorado River at Lees Ferry, Arizona Natural Flow Statistics for the Downscaled GCM Projected Scenario as Compared to Observed Flow

Median (line), 25th–75th percentile band (dark shading), 10th–90th percentile band (light shading), max/min (whiskers), and 1906–2007 observed (blue line).

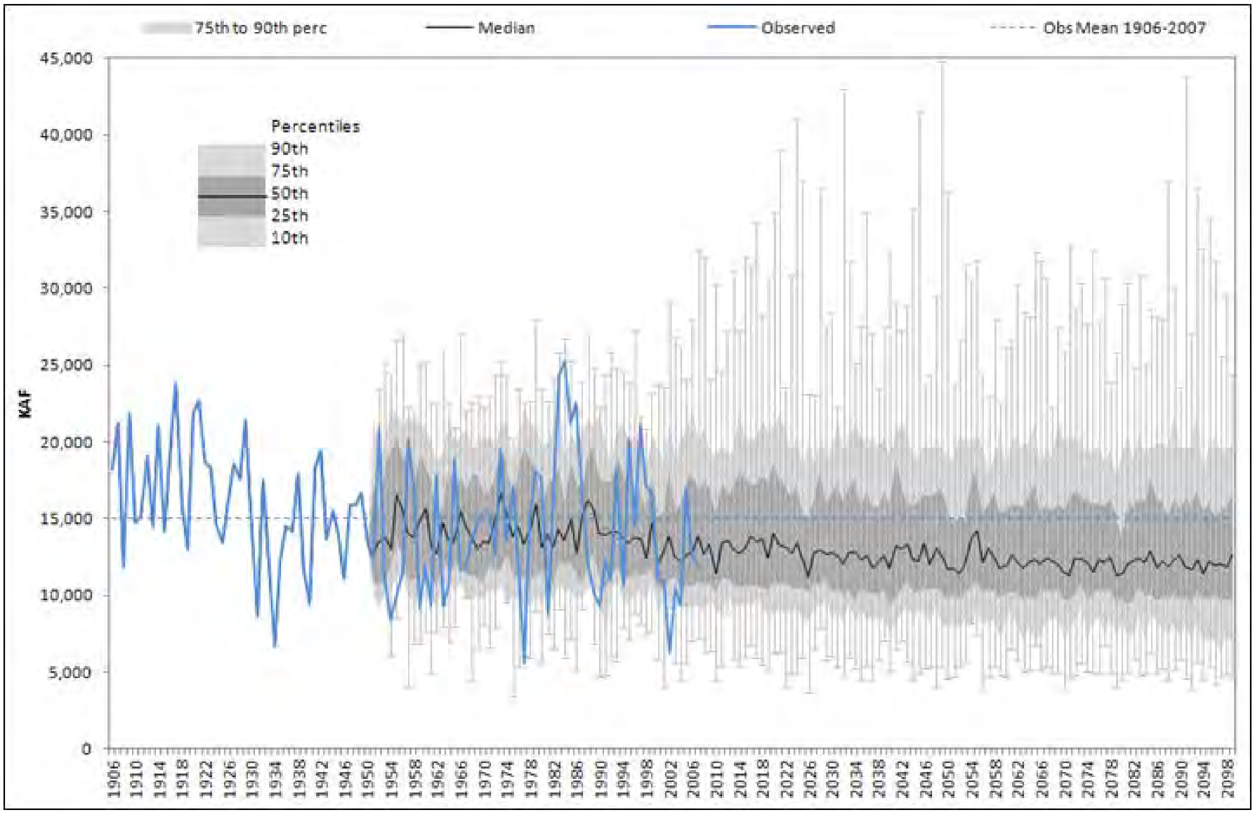
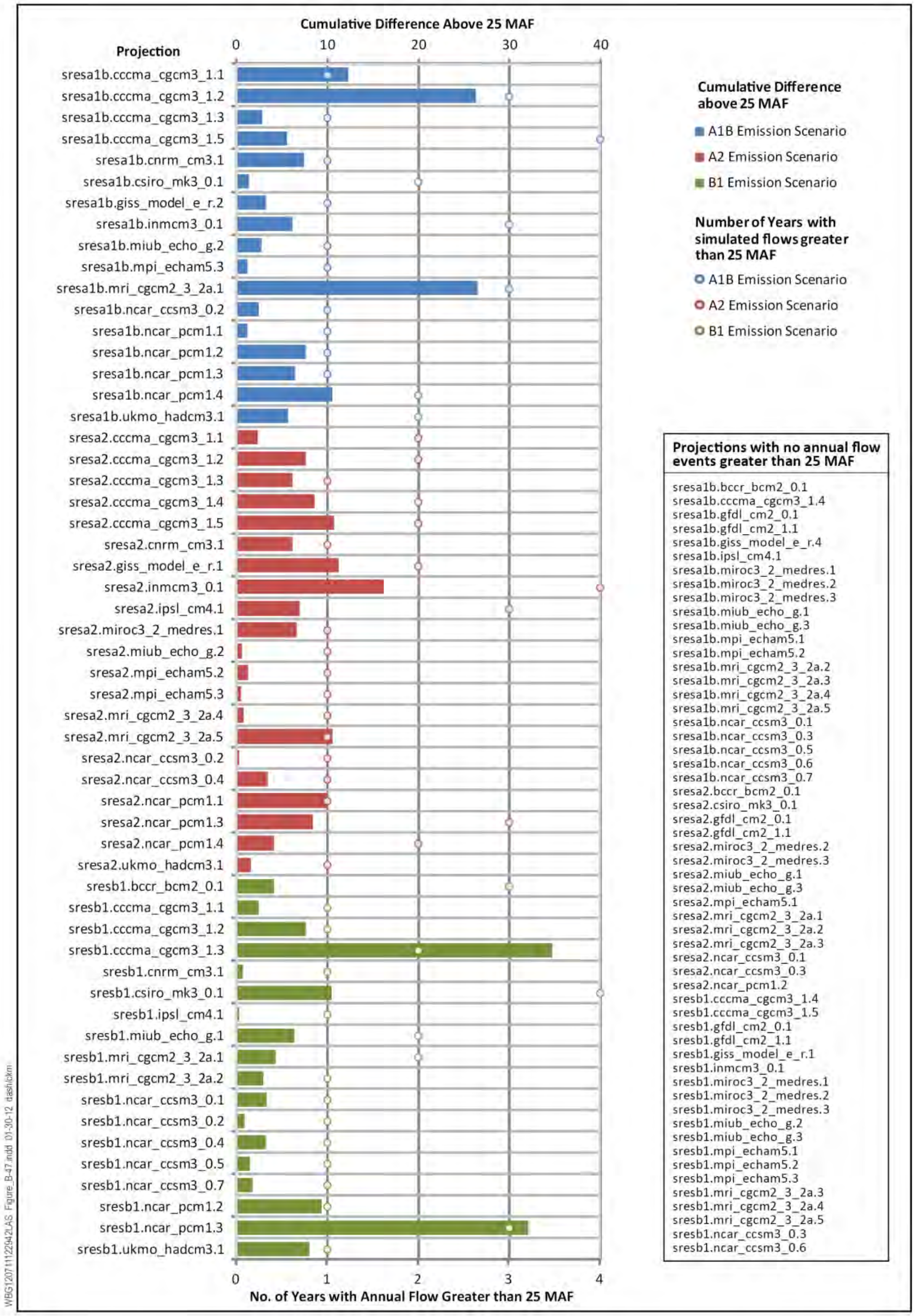


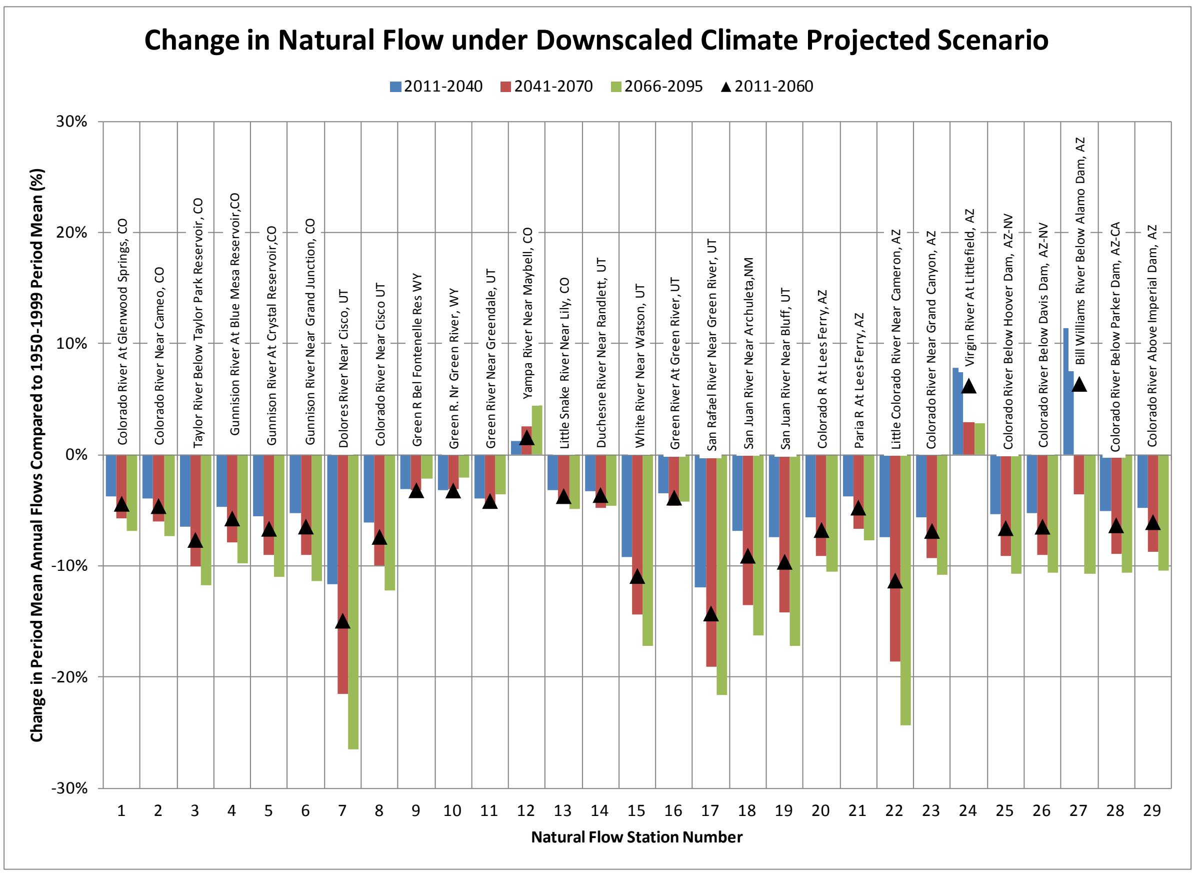
FIGURE B-47
Cumulative Difference from Simulated Annual Maximum Flow and 25 maf (bar) and Total No. of Years that Exceed 25 maf (dot) for Colorado River at Lees Ferry, Arizona for 112 Downscaled Projections for the Period 2011–2060



The analysis concluded that it is a rare occurrence for a projection to exceed 25 maf, but the potential is prevalent among the ensemble members regardless of emission scenario. The GCMs ECHAM5, CCSM, MIROC, and Geophysical Fluid Dynamics Laboratory, however, stood out in producing the fewest of these events (see appendix B2).

Figure B-48 shows the mean annual percent change in natural flow for all 29 locations for four future periods as compared to the 50-year historical period of 1950 to 1999. The comparison here is not made to the observed 1906 to 2007 period, but rather to the historical VIC-simulated period such that any inherent model biases are incorporated in both VIC-simulated periods. The future periods reflect the Study period (2011 to 2060) and three 30-year periods extending throughout the 21st Century (2011 to 2040, 2041 to 2070, and 2066 to 2095) to provide the time evolution of the projected flow changes.

FIGURE B-48
Simulated Relative Change in Mean Annual Flows (Ensemble Mean) for the Study Period (2011–2060), and Three Future Periods (2011–2040, 2041–2079, and 2066–2095), Compared to 1950–1999 for each of the 29 Natural Flow Locations



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

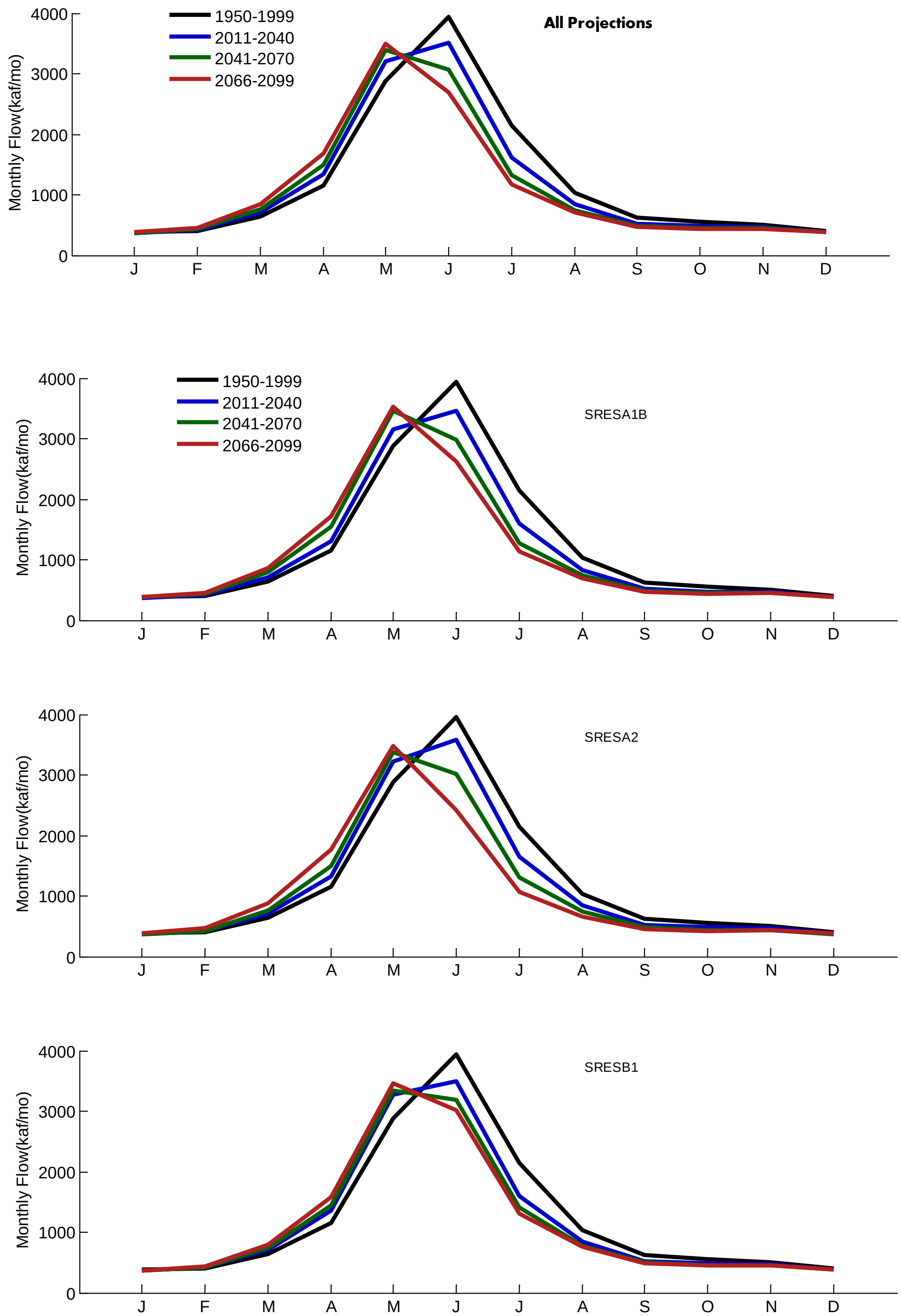
The implicit assumption made with respect to the SRES emission scenarios used to drive the GCMs in the Study is that they are equally likely (or unlikely) and that they can be used in a multi-model ensemble. Climate projections through mid-century are dominated by the choice of GCM rather than individual emission scenarios. Table B-1 presents the range of projected change in Colorado River at Lees Ferry, Arizona streamflow associated with specific SRES emission scenarios, as compared to the ensemble of all emission scenarios. VIC simulations indicate streamflow reductions for all three SRES emission scenarios, and difference of less than 2 percent between emission scenario groupings for time periods covered in the Study. These results are expected since the climate system responds relatively slowly to changes in emissions. By late century, the differences between simulated streamflows across emission scenarios become substantially larger, reflecting both the response time of the climate system and the higher emissions. During the first period indicated in table B-1, it is noteworthy that the greatest streamflow reduction occurs under the A1B scenario. While the GHG emissions in this scenario fall between the A2 and B1 scenarios in the distant future, they actually represent the highest emission scenario (of the three) through about 2020 (see appendix B2). By the second and third periods (mid-century and beyond) the streamflow changes between emission scenarios are more intuitive with the general emission pathways.

TABLE B-1
Percentage Change in Mean Flow with Respect to Historical Mean (1950–1999) at the Colorado River at Lees Ferry, Arizona

	2011–2040	2041–2070	2066–2095	2011–2060
All Projections	-5.6	-9.1	-10.5	-6.8
SRESB1	-5.2	-7.9	-8.0	-6.0
SRESA1B	-6.7	-9.1	-10.5	-7.7
SRESA2	-4.9	-10.3	-13.2	-6.5

While annual flows show decreases and likely some expansion in variability, monthly flows exhibit a significant shift in timing. Figure B-49 shows the simulated mean monthly flows from the climate projections for the Colorado River at Lees Ferry, Arizona compared to the observed monthly flows. Commensurate with the seasonal changes in temperature, precipitation, and hydrologic processes, after 2025, the peak streamflow occurs about one month earlier (from June through May) and is approximately 500 thousand acre-feet (kaf) lower. In addition, increases occur in winter streamflow, while substantial reductions occur in spring and summer. The wintertime increases are likely associated with increased precipitation in the Upper Basin, while spring and summer decreases are likely associated with earlier melt of the snowpack and reduced precipitation patterns. Prior to the mid-century it appears that the transition to

FIGURE B-49
Comparison of Observed and Future Simulated Mean Monthly Flows at Colorado River at Lees Ferry, Arizona



earlier runoff is underway with increasing May flows and decreases in June flows, but the full monthly shift has not yet occurred. The lower panels of figure B-49 also indicate that there is no substantial difference in the monthly timing trends between emission scenarios.

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

Figure B-50 illustrates the frequency and magnitude of both deficit and surplus spells. The inset figure shows the frequency occurrence of a specific spell length across all projections. The median exceedance probability of a surplus spell longer than 0 years is 30 percent, indicating that, when as measured against the 1906 to 2007 mean annual flow of 15 maf, about a third of the years in the future would be considered to not be a deficit. In addition, deficit length may extend greater than 20 years (indicated by the 90th percentile deficit length), as compared to the recent 9-year deficit. Under the Downscaled GCM Projected scenario (at the ensemble median) a 9-year deficit may occur up to 20 percent of the time and result in a cumulative deficit of 30 to 40 maf. The recent 9-year deficit is estimated to have a cumulative deficit of more than 28 maf. The results also suggest that under some climate projections, sustained periods of dryness will occur (deficit lengths greater than 50 years). Most projections result in long-term mean annual flows that are less than the 15 maf observed mean. The future climate essentially arrives at a new mean state. Thus deficits may need to be evaluated against the projection-specific, long-term mean to reflect this new inter-annual variability about the new mean.

Figure B-51 is identical to figure B-50 except that the threshold for deficit and surplus is determined from the projection-specific, long-term mean, rather than the observed mean. The drought depiction is considerably different under these conditions. As expected, deficit and surplus frequencies are roughly equal. In addition, deficit spell lengths do not exceed 17 years and are a maximum of 8 years at the median of the projections. Deficit magnitudes at the 9-year deficit remain in the 18 to 40 maf range. Under this perspective, the inter-annual variability is not substantially different than the recent observed period, but rather the Downscaled GCM Projected means are significantly reduced, leading to the perspective of relatively sustained deficit when measured against recent observed flows. There is no absolute correct perspective; thus, both methods are presented here.

FIGURE B-50
Simulated Deficit and Surplus Spell Length and Magnitude for All 112 Climate Projections
(Threshold Defined as 1906–2007 Mean Annual Flow ~15 maf)

Box plots show the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).

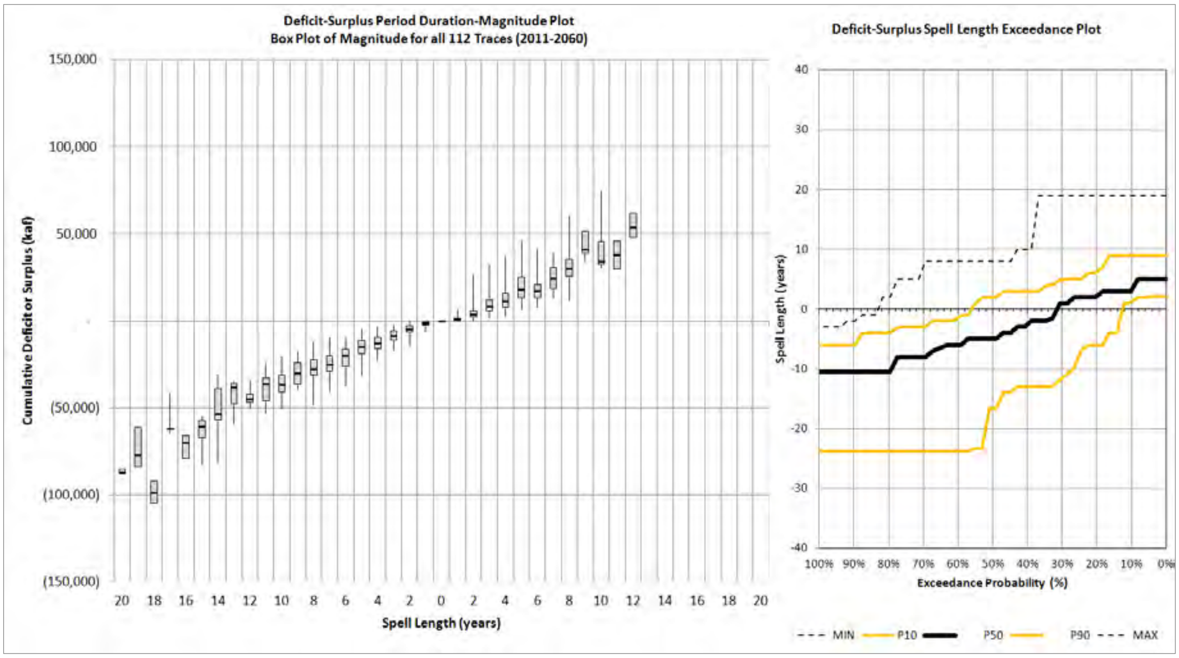
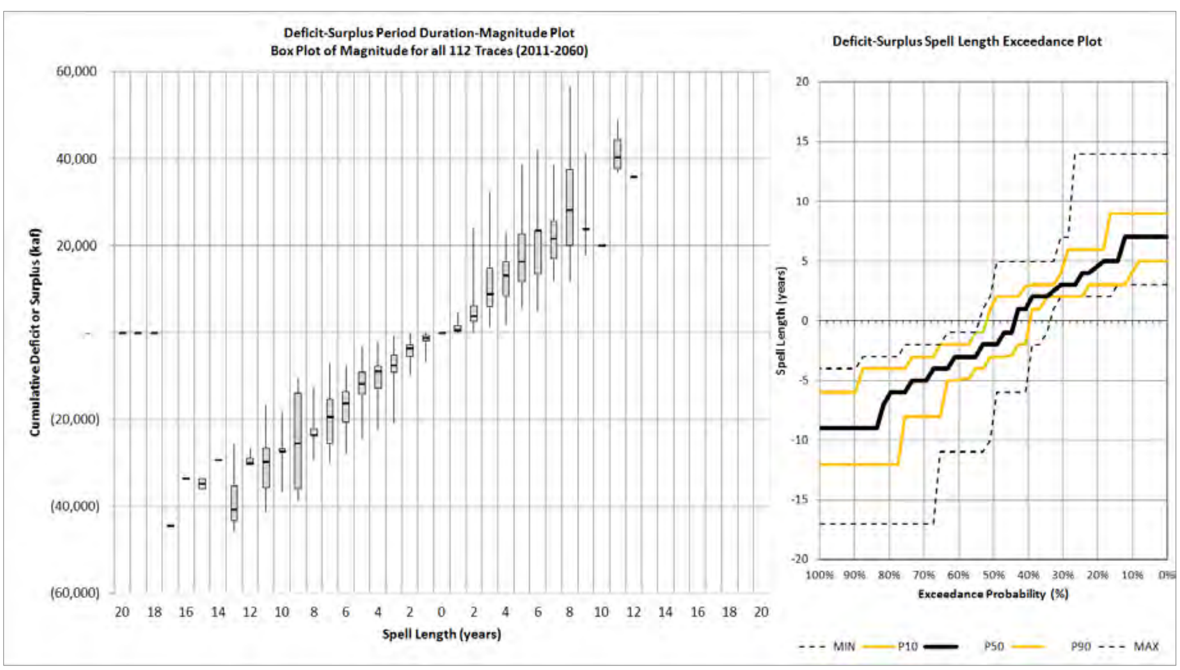


FIGURE B-51
Simulated Deficit and Surplus Spell Length and Magnitude for all 112 Climate Projections (Threshold Defined as Individual Projection Mean for 2011–2060)

Box plots show the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).



9.0 Comparison of Future Supply Scenarios

The water supply assessment described in this report includes four distinct supply scenarios that attempt to bracket the range of conditions that might be experienced over the next 50 years. The scenarios include direct use of the observed record (Observed Resampled scenario), direct use of the paleo reconstructions (Paleo Resampled scenario), blends of observed and paleo sequences (Paleo Conditioned scenario), and use of future climate projections and hydrologic modeling (Downscaled GCM Projected scenario). Figure B-52 shows the range of annual flows for the Colorado River at Lees Ferry, Arizona for each of the scenarios in a four-panel series.

The Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios have similar mean annual flows and a similar range of annual variability. The Paleo Resampled scenario contains individual years of flows lower than Observed Resampled, but a narrower band of variability within the inter-quartile range. The Paleo Conditioned scenario, by design, includes a similar range of annual flows as the Observed Resampled. The Downscaled GCM Projected scenario reflects possible changes in climate beyond what occurred historically and has lower mean annual flows while expanding the annual variability range through increased maximum annual flows. Mean annual natural flows for the Colorado River at Lees Ferry, Arizona range from 14.7 to 15.0 maf for the Observed Resampled, Paleo Resampled, and Paleo Conditioned scenarios. The Downscaled GCM Projected scenario results in mean annual flows of approximately 13.7 maf.

Each supply scenario includes multiple realizations, resulting in a range of flow statistics. Figure B-53 graphically depicts these annual flow statistics. The range of mean flows is greatest under the Downscaled GCM Projected scenario, with the inter-quartile range spanning roughly 12.5 to 15 maf and the absolute range covering 10 to 17 maf. Especially with respect to the use of climate projections, the ensemble mean or median should be considered more useful than any individual projections. This ensemble mean or median has been shown to perform better than any individual projection against a range of historical climate metrics and variability and trend significance, largely due to the cancelling out of natural internal GCM model variability and cancelling out of individual model errors (see Gleckler et al. [2008], and Pierce et al. [2009], for a more-complete discussion of this topic). The Paleo Resampled scenario, despite the large absolute range, has a smaller standard deviation than the other scenarios due to the tightness of the bulk of the realizations. Skew is a measure of the shape of the annual flow distribution. A skew of zero implies a normal distribution, in which wetter years and magnitudes are evenly balanced with drier years. Most scenarios have a positive skew, suggesting a bias to the drier side of the distribution. This is particularly noticeable in the Downscaled GCM Projected scenario. The Paleo Resampled scenario has the highest year-to-year correlation as measured by the backward lag-1 correlation. This high degree of correlation is attributable in part to the method used to develop the reconstructions. The minimum annual flows are fairly consistent across the scenarios, with the Paleo Resampled scenario exhibiting the most extreme low-flow condition. The Downscaled GCM Projected scenario exhibits a range of maximum annual flows well beyond those seen in any of the other scenarios.

FIGURE B-52
Annual Colorado River at Lees Ferry, Arizona Natural Flow Time Series for Supply Scenarios
Median in bold black line, inter-quartile range in dark shading, 10th–90th percentile range in light shading, selected individual sequence in bold colored line, max/min as whiskers, and 1906–2007 observed max/min (dashed lines).

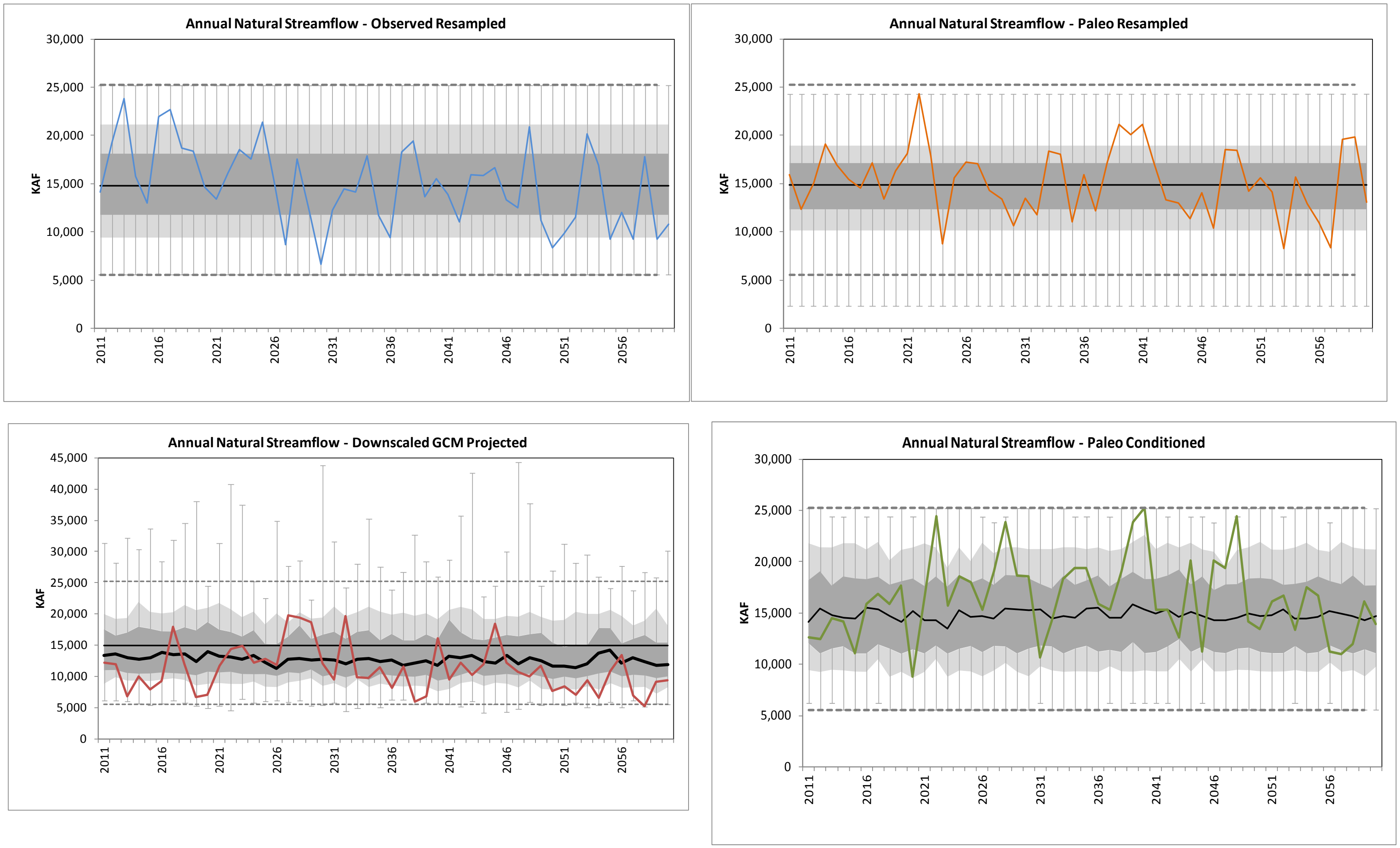


FIGURE B-53
Summary Statistics for Annual Colorado River at Lees Ferry, Arizona Natural Flows for Supply Scenarios (for 2011–2060)
Figure shows the median (dash), 25th–75th percentile band (box), and max/min (whiskers).

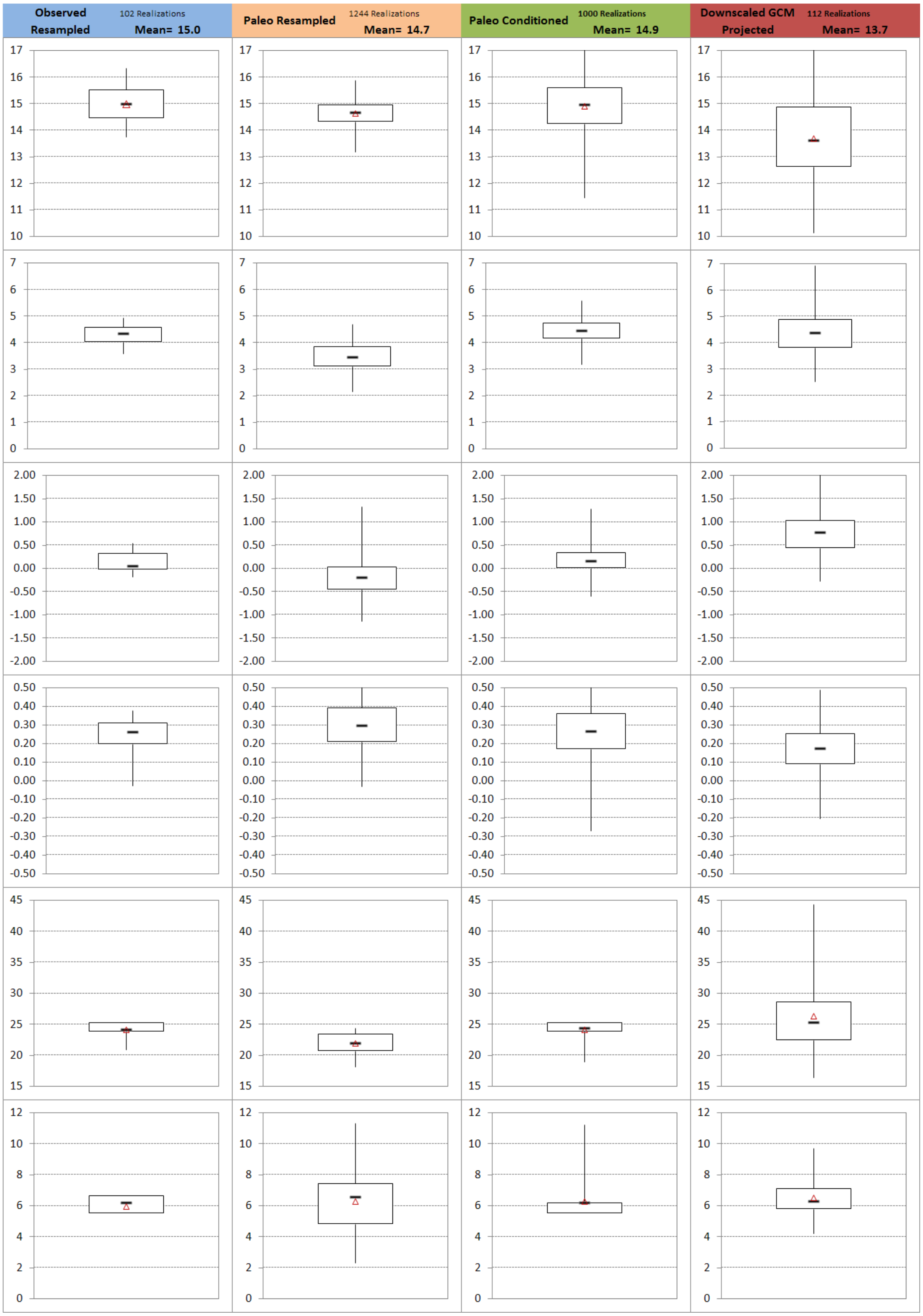


Figure B-54 provides a side-by-side comparison of each of the scenarios over the study horizon and the monthly flow range. Again, the Downscaled GCM Projected scenario demonstrates both higher high flows and lower low flows, measured as a 5-year average. This range, combined with the reduced mean annual natural flows in this scenario, makes the Downscaled GCM Projected scenario likely the most challenging supply condition within which to manage the Basin. The figure also shows that the monthly variability of the Downscaled GCM Projected scenario is significantly larger than any other scenario. This is particularly true in the winter and spring, when the Upper Basin hydrologic processes are most active and subject to change under climate warming. The shift in peak flow timing from June through May is apparent in figure B-55, and becomes more pronounced when analyzing results for the later 30-year time periods (table B-3).

FIGURE B-54
Annual Colorado River at Lees Ferry, Arizona 5-Year Natural Flow Time Series (top) and Monthly Variability across Supply Scenarios (bottom) (for 2011–2060)

Figure shows the median (dash), 25th–75th percentile band (box), and max/min (whiskers).

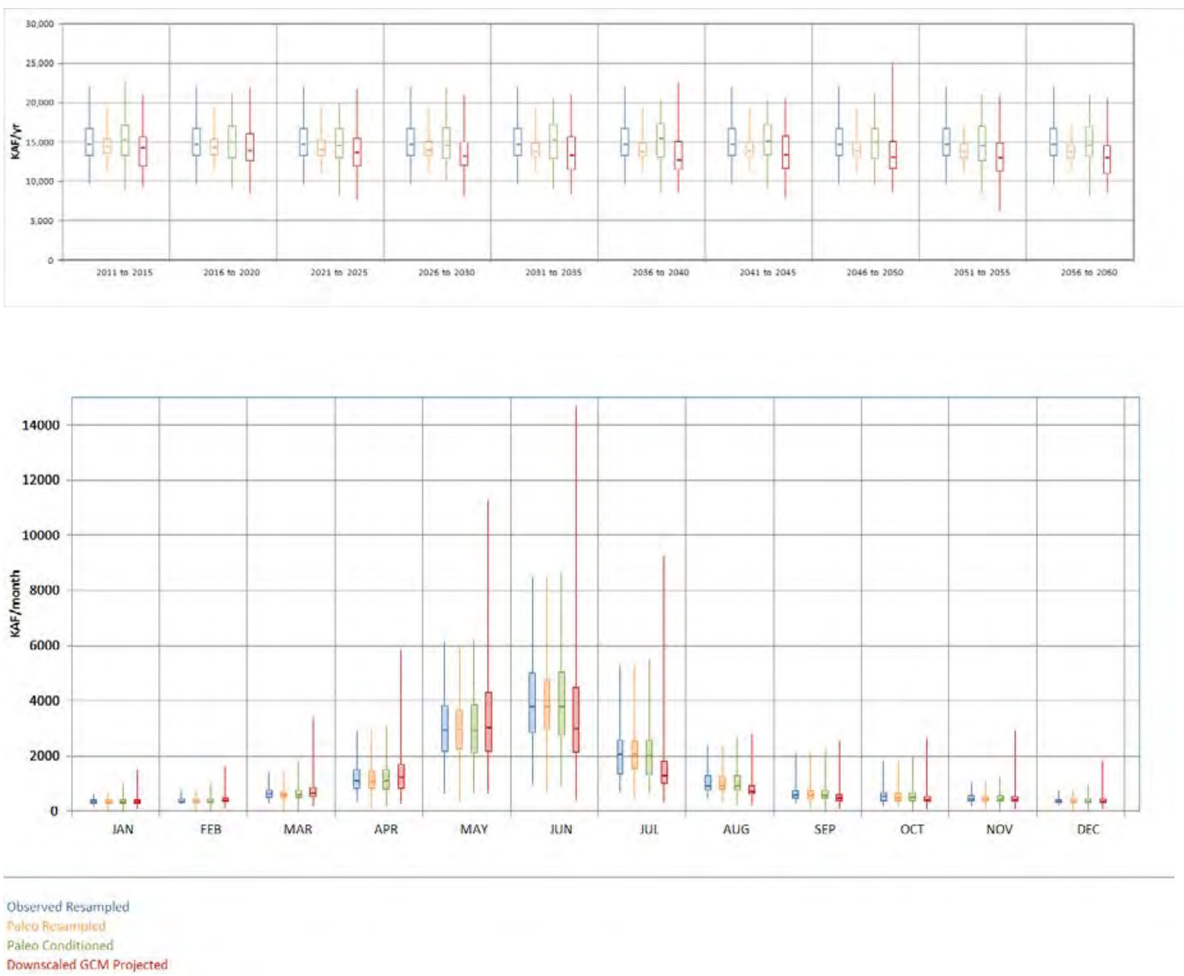
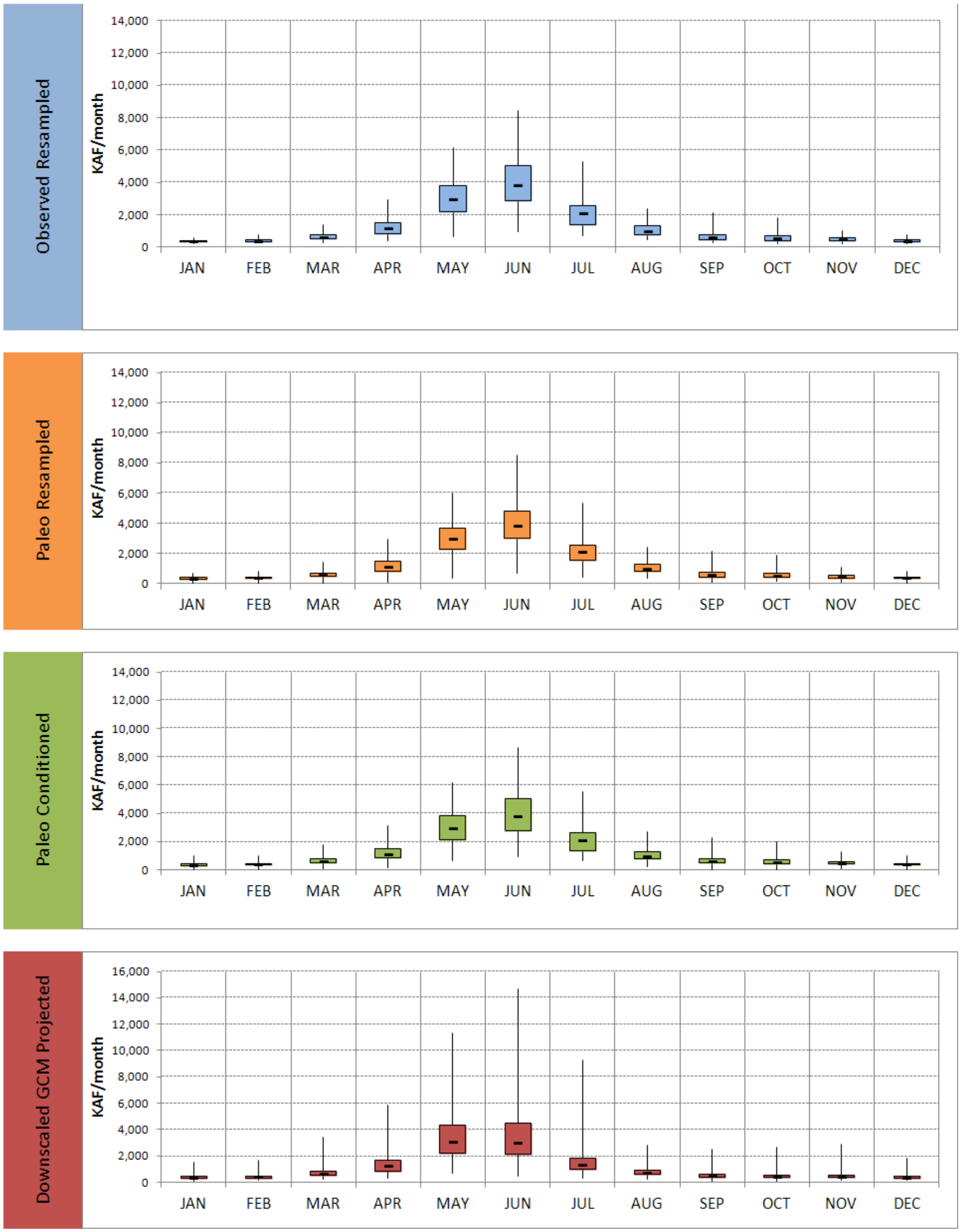


FIGURE B-55
Monthly Colorado River at Lees Ferry, Arizona Natural Flow Variability for Supply Scenarios (for 2011–2060)
Figure shows the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).



The inter-annual variability of streamflow across the scenarios is characterized by determining the frequency, duration, and magnitude of deficit and surplus periods. Figure B-56 is a four-panel figure showing the length and magnitude of such spells. For example, the maximum length of sustained deficit through 2007 in the Observed Resampled scenario was 8 years (note that this length would be 9 years if the observed record extended through 2010), while the maximum sustained surplus is 7 years. In comparison, the Paleo Resampled, Paleo Conditioned, and Downscaled GCM Projected scenarios all produce deficit periods of 15 years or longer. The maximum deficit accumulated is approximately 60 maf over the 15 years of deficit (both Paleo Conditioned and Downscaled GCM Projected scenarios). However, the reduced mean annual flow in the Downscaled GCM Projected scenario causes many of the realizations to be in a sustained deficit using the recent observed flows as the measure.

FIGURE B-56
Frequency, Duration, and Magnitude of Deficit and Surplus Periods for Supply Scenarios (for 2011–2060)
Top figures (left to right) are the Observed Resampled and Paleo Resampled scenarios. Bottom figures (left to right) are the Paleo Conditioned and Downscaled GCM Projected scenarios. Box plots show the median (dash), 25th–75th percentile band (shading), and max/min (whiskers).

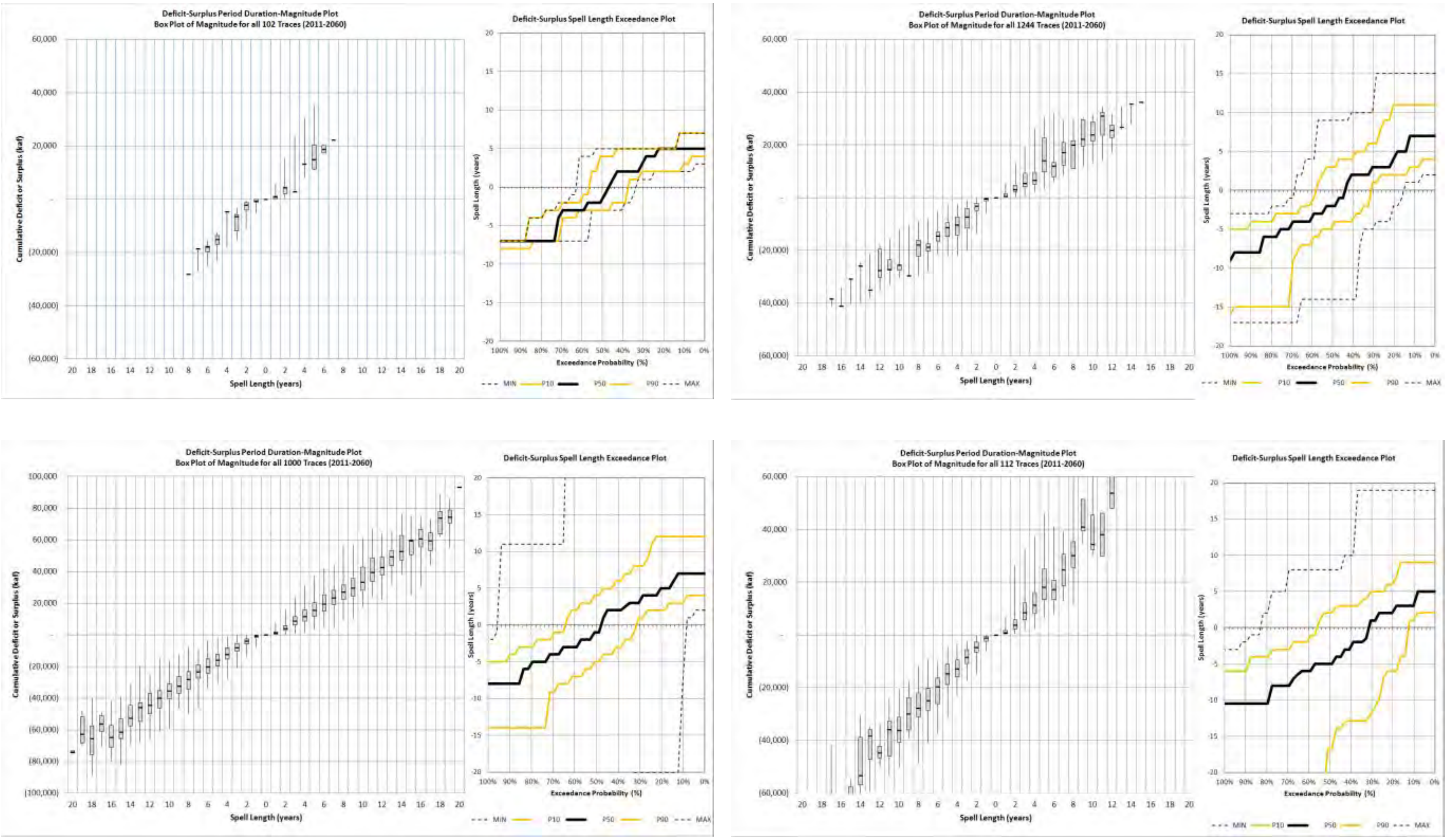


Table B-2 summarizes the key statistics for each water supply scenario and generally provides a tabular presentation of the information presented in the figures in this section. Similarly, table B-3 summarizes the annual and monthly statistics for the Downscaled GCM Projected scenario for three distinct future periods (2011 to 2040, 2041 to 2070, and 2066 to 2095) to assist in the evaluation of temporal trends. It should be noted that the last of these three periods is beyond the Study period, but is shown to assist in understanding trajectory of projected changes. Under this scenario, mean annual flows are projected to continue to decrease over time (from -7.5 percent around 2025 to -10.9 percent around 2055, to -12.4 percent around 2080) as compared to the 1906 to 2007 mean. At the same time, the shift in peak streamflow timing evolves from a current peak in June to an eventual peak in May due to earlier snowmelt and increased rain-to-snow ratios in response to warming.

TABLE B-2
Summary of Key Streamflow Statistics for Each Water Supply Scenario for the Period 2011–2060

	Statistic	Scenario			
		Observed Resampled	**Paleo Resampled**	**Paleo Conditioned**	**Downscaled GCM Projected**
Annual (Water Year)	Average Annual Flow (maf)	15.0	14.7	14.9	13.7
	Percent Change from Long-Term Mean (1906–2007)	0%	-2%	-1%	-8.7%
	Median (maf)	15.0	14.7	15.0	13.6
	25th Percentile (maf)	14.5	14.3	14.2	12.6
	75th Percentile (maf)	15.5	15.0	15.6	14.9
	Minimum Year Flow (maf)	5.6	2.3	5.6	4.2
	Maximum Year Flow (maf)	25.2	24.3	25.2	44.3
Monthly	Peak Month	June	June	June	June
	Peak Month Mean Flow (kaf)	4,007	3,914	4,000	3,393
	Peak Month Maximum Flow (kaf)	8,467	8,531	8,678	14,693
	Month at Which Half of Annual Flow (Water Year) is Exceeded	June	June	June	June
Deficit Periods[1]	Maximum Deficit (maf)	28.2	38.4	98.5	246.1
	Maximum Spell Length (years)	8	17	24	50
	Intensity (Deficit/Length) (maf/year) [median]	3.5	2.3	4.1	7.4
	Frequency of 5+ Year Spell Length (Percent) [median]	22%	30%	25%	48%
	Maximum 8-year Deficit (longest in 1906–2007 observed record, maf)	28.2	29.8	50	48.6
Surplus Periods[2]	Maximum Surplus (maf)	22.2	36.2	88	74.7
	Maximum Spell Length (years)	7	15	25	19
	Intensity (Surplus/Length) (maf/year)	3.2	2.4	3.5	13.2
	Frequency of 5+ Year Spell Length (Percent)	28%	15%	18%	<1%
	Maximum 7-year Surplus (longest in 1906–2007 observed record, maf)	22.2	29.2	44	39.2

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

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

TABLE B-3
Summary of Annual and Monthly Streamflow Statistics for the Downscaled GCM Projected Scenario for the 3 Future 30 Year Time Periods: 2011–2040 (2025), 2041–2070 (2055), and 2066–2095 (2080)

	Statistic	**Downscaled GCM Projected 2011–2040 (2025)**	**Downscaled GCM Projected 2041–2070 (2055)**	**Downscaled GCM Projected 2066–2095 (2080)**
Annual (Water Year)	Average Annual Flow (maf)	13.9	13.4	13.1
	Percent Change from Long-Term Mean (1906–2007)	-7.5%	-10.9%	-12.4%
	Median (maf)	13.8	13.3	13.4
	25th Percentile (maf)	12.8	12.0	11.2
	75th Percentile (maf)	15.1	14.6	14.5
	Minimum Year Flow (maf)	4.4	3.9	3.7
	Maximum Year Flow (maf)	43.8	44.3	44.3
Monthly	Peak Month	June	May	May
	Peak Month Mean Flow (kaf)	3,535	3,388	3,495
	Peak Month Maximum Flow (kaf)	14,693	10,830	12,991
	Month at Which Half of Annual Flow (Water Year) is Exceeded	June	May	May

The last time period is beyond the Study period, but is shown for informational purposes.

10.0 Summary and Limitations

This report documents the current and future water supply assessment for the Study. The research and development program initiated by Reclamation in 2004 resulted in the development of the Paleo Resampled and Paleo Conditioned scenarios. These scenarios are described in appendix N of the 2007 Interim Guidelines Final EIS (Reclamation, 2007), as is the Observed Resampled scenario. The Downscaled GCM Projected scenario is the newest addition to the set of scenarios and has not been previously used in any Reclamation long-term planning activities. The VIC modeling associated with the projected climate forcings suggests changes in streamflows resulting from this scenario are consistent with past efforts, particularly that of Christensen and Lettenmaier (2007).

The streamflow bias correction that has been included in this report compensates for biases in climate and hydrologic data as well as for biases in the hydrology model (VIC) structure. This step is important for the use of results other than “change” metrics in subsequent analyses. However, in evaluating biases and VIC model performance, the need for model calibration at finer resolutions is found to be a necessary next step and will reduce the level of bias correction needed in the future. Care should be taken in attempting to apply the “raw” VIC results for smaller watersheds in the Basin. The improvements in hydrologic model calibration and application should parallel progress in climate modeling and methods to develop higher-resolution climate information.

The role of snowpack development and melt, ET, and soil moisture are found to be very important in determining the available supply in the Basin. However, limited Basin-wide data are available to better understand these dynamics. The elevational sensitivity of snowpack, effect of warming and increased carbon dioxide on ET, and the role of summer and fall soil moisture on water supply are areas in need of further study.

In addition, newer GCMs and downscaling techniques will soon be available under the IPCC Fifth Assessment Report. The improved resolution and model physics of some of the new GCMs may refine patterns of precipitation changes (such as the increases in the Green River Basin and Upper Colorado, and monsoonal effects in the Lower Basin).

11.0 References

AchutaRao, K. M., and K. R. Sperber. 2002. “Simulation of the El Niño Southern Oscillation: Results from the Coupled Model Intercomparison Project.” *Climate Dynamics*, Vol. 19: 191-209, DOI 10.1007/s00382-001-0221-9.

AchutaRao, K. M., and K. R. Sperber. 2006. “ENSO Simulation in Coupled Ocean-Atmosphere Models: Are the Current Models Better?” *Climate Dynamics*, Vol. 27: 1-15, DOI: 10.1007/s00382-006-0119-7.

Andreadis, K. M., and D. P. Lettenmaier. 2006. “Trends in 20th-Century Drought over the Continental United States.” *Geophysical Research Letters*, 33, L10403, DOI:10.1029/2006GL025711.

Becker, E.J., E.H. Berbery, and R.W. Higgins. 2011. “Modulation of Cold-Season U.S. Daily Precipitation by the Madden–Julian Oscillation.” *J. Climate*, 24, 5157–5166.

Bond, N. A., and G.A. Vecchi. 2003. “The influence of the Madden–Julian oscillation on precipitation in Oregon and Washington.” *Wea. Forecasting*, 18, 600–613.

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

Bureau of Reclamation (Reclamation). 2011a. Colorado River Natural Flow Data. Retrieved from http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html.

Bureau of Reclamation (Reclamation). 2011b. *Literature Synthesis on Climate Change Implications for Water and Environmental Resources*.

Bureau of Reclamation (Reclamation). 2011c. *SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011*.

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.” *Proceedings of the National Academy of Sciences*, 107(50), 21271-21276, DOI: 10.1073/pnas.0912391107.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and, D.H. Peterson. 2001. “Changes in the Onset of Spring in the Western United States.” *Bulletin of the American Meteorological Society*, 82, 399–415.

Cayan, D.R., K.T. Redmond, , and L.G. Riddle. 1999. "ENSO and Hydrologic Extremes in the Western United States." *Journal of Climate*, 12, 2881-2893.

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." *Hydrology and Earth System Sciences*, 11, 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." *Climatic Change*, 62, 337–363.

Clark, M.P., M.C. Serreze, and G.J. McCabe. 2001. "The Historical Effect of El Niño and La Niña Events on the Seasonal Evolution of the Mountain Snowpack in the Columbia and Colorado River Basins." *Water Resources Research*, 37, 741-757.

Colorado Water Conservation Board. 2010. *Colorado River Water Availability Study*. Draft Report.

Collins, M., S. An, W. Cai, A. Ganachaud, E. Guilyardi, F. Jin, M. Jochum, M. Lengaigne, S. Power, A. Timmermann, G. Vecchi, and A. Wittenberg. 2010. "The Impact of Global Warming on the Tropical Pacific Ocean and El Niño." *Nature*, 3, 391-397. doi: 10.1038/ngeo868

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.*, DOI: 10.1029/2011GL049660.

Diaz, H.F., and G.N. Kiladis. 1992. "Atmospheric Teleconnections Associated with the Extreme Phases of the Southern Oscillation." Diaz, H.F., and V.A. Markgraf (eds.). *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*.

Edwards, L. M., and K.T. Redmond. 2005. "Climate Factors on Colorado River Basin Water Supply." In *Colorado River Basin Climate: Paleo, Present, Future*. Special publication for Association of California Water Agencies and Colorado River Water Users Association Conferences, California Department of Water Resources, pp. 14-22.

Fassnacht, S. R. 2006. "Upper Versus Lower Colorado River Sub-basin Streamflow: Characteristics, Runoff Estimation, and Model Simulation." *Hydrological Processes,* 20, 2187–2205.

Gleckler, P.J., K.E. Taylor, and C. Doutriaux. 2008. "Performance Metrics for Climate Models." *Journal of Geophysical Research* 46, DOI: 10.1019/2007JD008972.

Gleick, P.H. 1987. "Climatic changes, water resources, and institutional responses: A look at the United States, Mexico, and the Colorado River." In the Proceedings of the Symposium on Climatic Change in the Southern United States: Future Impacts and Present Policy Issues (May 28-29, 1987). U.S. Environmental Protection Agency/University of Oklahoma. pp. 450–465.

Groisman, P. Ya., R.W. Knight, and T.R. Karl. 2001. "Heavy Precipitation and High Streamflow in the Contiguous United States: Trends in the Twentieth Century." *Bulletin of the American Meteorological Society*, 82, 219–246.

Gutzler, D.S., H.K Kim, R.W. Higgins, H. Juang, M. Kanamitsu, K. Mitchell, K. Mo, P. Pegion, E. Ritchie, J.K. Schemm, S. Schubert, Y. Song, and R. Yang. 2005. "The North American Monsoon Model Assessment Project: Integrating numerical modeling into a field-based process study." *Bulletin of the American Meteorological Society* 86: 1423–1429.

Hamlet, A.F., and D.P. Lettenmaier. 1999. "Effects of climate change on hydrology and water resources objectives in the Columbia River Basin." *Journal of the American Water Resources Association*, 35(6),pp.1597-1625.

Hamlet, A. F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier. 2005. "Effects of Temperature and Precipitation Variability on Snowpack Trends in the Western United States." *Journal of Climate*, 18, 4545–4561.

Hamlet, A.F, E.P. Salathé, and P. Carrasco. 2010. *Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies*.

Hidalgo, H., T. Piechota, and J. Dracup. 2009. "Alternative Principal Components Regression Procedures for Dendrohydrologic Reconstructions." *Water Resources Research*, Vol. 45, W06417, DOI:10.1029/2008WR007201.

Hirschboeck, K.K., Meko, D.M. 2005. *A Tree-Ring Based Assessment of Synchronous Extreme Streamflow Episodes in the Upper Colorado & Salt-Verde-River Basins – Final Report*.

Hoerling, H., D.P. Lettenmaier, D. Cayan, and B. Udall. 2009. "Reconciling Projections of Colorado River Streamflow." *Southwest Hydrology*. May/June.

Hu, Q., and S. Feng. 2010. "Influence of the Arctic oscillation on central United States summer rainfall." *J. Geophys. Res.*, 115, D01102. DOI: 10.1029/2009JD011805.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Emissions Scenarios*. Special Report of the Intergovernmental Panel on Climate Change [Nakicenovic, N., and R. Swart (eds.)].

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Quin, M. Manning, Z., Chen, M. Marquis, K.B. Averyt, , M. Tignor, and H.L. Miller. (eds.)].

Lee, T., J.D. Salas, and J. Keedy. 2006. *Simulation Study for the Colorado River System Utilizing a Disaggregation Model*.

Liang, X., D.P. Lettenmaier, and E.F. Wood. 1996. *Surface Soil Moisture Parameterization of the VIC-2L Model: Evaluation and Modification*.

Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges. 1994. "A Simple Hydrologically Based Model of Land Surface Water and Energy Fluxes for General Circulation Models." *Journal of Geophysical Research*, Vol. 99, 14415–14428.

Lin, J., B.E. Mapes, K.M. Weickmann, G.N. Kiladis, S.D. Schubert, M.J. Suarez, J.T. Bacmeister, and M. Lees. 2008. "North American monsoon and convectively coupled equatorial waves simulated by IPCC AR4 Coupled GCMs." *J. Climate*, 21:2919–2937.

Lohmann, D., R. Nolte-Holube, and E. Raschke. 1996: "A large-scale horizontal routing model to be coupled to land surface parameterization schemes." *Tellus*, 48, 708–721.

Lohmann, D., E. Raschke, B. Nijssen, and D.P. Lettenmaier. 1998. "Regional Scale Hydrology: I. Formulation of the VIC-2L Model Coupled to a Routing Model." *Hydrological Sciences Journal*, 43, 131–141.

Maurer, E. P., L. Brekke, T. Pruitt, and P.B. Duffy. 2007. "Fine-Resolution Climate Projections Enhance Regional Climate Change Impact Studies." *Eos, Transactions, American Geophysical Union*, 88 (47), 504.

Maurer, E.P. 2007. "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California under two emissions scenarios." *Climatic Change*, Vol. 82, No. 3-4, 309-325, DOI: 10.1007/s10584-006-9180-9.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States." *Journal of Climate*, 15(22), 3237-3251.

McCabe, G.J., D.M. Wolock. 1999a. "General circulation model simulations of future snowpack in the western United States." *Journal of the American Water Resources Association*, Vol. 35, 1473–1484.

McCabe, G.J., D.M. Wolock. 1999b. "Estimates of runoff using water-balance and atmospheric general circulation models" [abst.]. *Journal of the American Water Resources Association*, Vol. 35(6), 1341–1350.

McCabe, G.J., D.M. Wolock. 2002. "A Step Increase in Streamflow in the Conterminous United States." *Geophysical Research Letters*, 29, 2185, DOI:10.1029/2002GL015999.

McCabe, G.J., M.A. Palecki, and J.L. Betancourt. 2004. "Pacific and Atlantic Ocean Influences on Multi-Decadal Drought Frequency in the United States." *Proceedings of the National Academy of Sciences*, 101, 4136–4141.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughs, and M.W. Salzer. 2007. "Medieval Drought in the Upper Colorado River Basin." *Geophysical Research Letters*, 34(5), L10705, DOI: 10.1029/2007GL029988.

Miller, W.P., and T.C. Piechota. 2008. "Regional Analysis of Trend and Step Changes Observed in Hydroclimatic Variables around the Colorado River Basin." *Journal of Hydrometeorology*, 9(5), 1020, DOI:10.1175/2008JHM988.1.

Mo, K.C., J.E. Schemm, and S. Yoo. 2009. "Influence of ENSO and the Atlantic Multi-Decadal Oscillation on Drought over the United States." *Journal of Climate*, 22(22), 5962–5982, DOI:10.1175/2009JCLI2966.1.

Mote, P.W. 2003. "Trends in snow water equivalent in the Pacific Northwest and their climatic causes." *Geophys. Res. Lett*., 30(12), 1601, DOI:10.1029/2003GL017258.

Mote, P. W. 2006. “Climate-Driven Variability and Trends in Mountain Snowpack in Western North America.” *Journal of Climate*, 19, 6209–6220.

Mote, P.M. Clark, and A. Hamlet. 2008. “Variability and Trends in Mountain Snowpack in Western North America.” 20th Conference on Climate Variability and Change. American Meteorological Society. New Orleans, Louisiana.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. “Declining Mountain Snowpack in Western North America.” *Bulletin of the American Meteorological Society*, 86, 39–49.

Nash, L.L., and P.H. Gleick. 1991. “The sensitivity of streamflow in the Colorado Basin to climatic changes.” *Journal of Hydrology*, Vol. 125, 221–241.

Nash, L., and P. Gleick. 1993. *The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation*. U.S. Environmental Protection Agency. EPA230-R-93-009.

National Oceanic and Atmospheric Administration (NOAA). 2011. Retrieved June 30, 2011, from http://www.ncdc.noaa.gov/oa/ climate/normals/usnormals.html.

National Research Council (NRC). 2007. *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*.

Nijssen, B., D.P. Lettenmaier, X. Liang, S.W. Wetzel, and E.F. Wood. 1997. “Streamflow simulation for continental-scale river basins.” *Water Resource Research*, 33, 711–724.

Nowak, K., J. Prairie, B. Rajagopalan, and U. Lall. 2010. “A nonparametric stochastic approach for multisite disaggregation of annual to daily streamflow.” *Water Resources Research*, 46.

Ouarda, T., J.W. Labadie, and D.G. Fontane.1997. “Index sequential hydrologic modeling for hydropower capacity estimation.” *J. of the American Water Resources Association*, 33(6), 1337–1349.

Pagano, T., and D. Garen. 2005. “A Recent Increase in Western U.S. Streamflow Variability and Persistence.” *Journal of Hydrometeorology*, 6, 173–179.

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.” Proceedings of the National Academy of Sciences on Climate Change and Water in Southwestern North America.

Pederson, G.T. , S.T. Gray, C.A.Woodhouse, J.L. Betancourt, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, L.J. Graumlich. 2011. “The Unusual Nature of Recent Snowpack Declines in the North American Cordillera.” *Science*, 333, 332 (2011).

Piechota, T. C., J. Timilsena, G.A. Tootle, and H. Hidalgo. 2004. “The Western U.S. Drought: How Bad is it?” *Eos, Transactions, American Geophysical Union*, 85, 301–308.

Pierce, D.W., T.P. Barnett, B.D. Santer, and P.J. Gleckler. 2009. “Selecting Global Climate Models for 12 Regional Climate Change Studies.” *Proceedings of the National Academy of Sciences*.

Prairie, J., K. Nowak, B. Rajagopalan, U. Lall, and T. Fulp. 2008. “A Stochastic Nonparametric Approach for Streamflow Generation Combining Observational and Paleoreconstructed Data.” *Water Resources Research*, Vol. 44, W06423, DOI: 10.1029/2007WR006684.

Redmond, K.T., and R.W. Koch. 1991. "Surface Climate and Streamflow Variability in the Western United States and Their Relationship to Large-Scale Circulation Indices." *Water Resources Research*, 27, 2381–2399.

Regonda, S.K., B. Rajagopalan, M.P. Clark, and J. Pitlick. 2005. "Seasonal Shifts in Hydroclimatology over the Western United States." *Journal of Climate*, 18, 372–384.

Sabo, J.L., S. Tushar, L.C. Bowling, G.H.W. Schoups, W.W. Wallender, M.E. Campana, K.A. Cherkauer, P.E. Fuller, W.L. Graf, J.W. Hopmans, J.S. Kominoski, C. Taylor, S.W. Trimble, R.H. Webb, and E.E. Wohl. 2010. "Climate Change and Water in Southwestern North America Special Feature: Reclaiming freshwater sustainability in the Cadillac Desert." *Proc Natl Acad Sci*, 107:21263–21270.

Salathé, E.P. 2005. "Downscaling simulations of future global climate with application to hydrologic modeling." *Int J Climatol*, 25, 419–436.

Seager, R. and G.A. Vecchi. 2010. "Greenhouse warming and the 21st century hydroclimate of southwestern North America." *Proc Natl Acad Sci*, 107, 21277–21282.

Stockton, C.W., and G.C. Jacoby. 1976. "Long-term Surface Water Supply and Streamflow Trends in the Upper Colorado River Basin." *Lake Powell Research Project Bulletin*, No. 18.

Webb, R.H., and J.L. Betancourt. 1992. *Climatic Variability and Flood Frequency of the Santa Cruz River, Pima County, Arizona*. U.S. Geological Survey. Water-Supply Paper 2379.

Wilby, R.L., L.E. Hay, and G.H. Leavesley. 1999. "A comparison of downscaled and raw GCM output: implications for climate change scenarios in the San Juan River Basin, Colorado." *Journal of Hydrology*, 225, 67–91.

Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier. 2002. "Long-Range Experimental Hydrologic Forecasting for the Eastern United States." *Journal of Geophysical Research-Atmospheres*, 107(D20), 4429.

Wood, A.W., L.R. Leun, V. Sridhar, and D.P. Lettenmaier. 2004. "Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs." *Climatic Change*, 15(62):189–216.

Woodhouse, C.A., and P.M. Brown. 2001. "Tree-ring evidence for Great Plains drought." *Tree-Ring Research*, 57:89–103.

Woodhouse, C.A., and J.J. Lukas. 2006. "Multi-Century Tree-Ring Reconstructions of Colorado Streamflow for Water Resource Planning." *Climatic Change*, 78, 293–315.

Woodhouse, C.A., S. Gray, and D. Meko 2006. "Updated Streamflow Reconstructions for the Upper Colorado River Basin." *Water Resources Research*, 42(5), W05415, DOI: 10.1029/2005WR004455.

Woodhouse, C.A., D.M. Meko, G.M. MacDonald., D.W. Stahle, and E.R. Cook. 2010. "A 1,200-year perspective of 21st century drought in southwestern North America." *Proc Natl Acad Sci*, 107, 21283–21288.

World Meteorological Organization. 2011. Retrieved from http://www.wmo.int/pages/index_en.html.

Yeh, S., and B.P. Kirtman. 2007. “ENSO Amplitude Changes Due To Climate Change Projections In Different Coupled Models.” *Journal of Climate*, 20(2), 203. DOI:10.1175/Jcli4001.1.

Yeh, S-W, J.S. Kug, B. Dewitte, M.H. Kwon, B.P. Kirtman, and F.F. Jin. 2009. “El Niño in a Changing Climate.” *Nature*, 461:511-U570.

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 was constrained by funding, timing, and technological and other limitations, and in some cases presented 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 developed and incorporated assumptions to further complete the Study. Where possible, a range of assumptions was typically 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.

Appendix C1
Water Demand Sub-Team Members

Appendix C1 — Water Demand Sub-Team Members

The information presented in *Technical Report C – Water Demand Assessment* is the outcome of a collaborative process involving representatives of numerous organizations.

A list of Water Demand Sub-Team members and their affiliations is presented below.

- Perri Benemelis, Arizona Department of Water Resources
- Jim Prairie, Bureau of Reclamation
- Greg Gates, CH2M HILL
- Ted Kowalski, Colorado Water Conservation Board
- Jennifer Pitt, Environmental Defense Fund
- Jason John, Navajo Nation
- John Whipple, New Mexico Interstate Stream Commission
- Tom Maher, Southern Nevada Water Authority
- Bill Hasencamp, The Metropolitan Water District of Southern California
- Don Ostler, Upper Colorado River Commission
- Andrew Hautzinger, U.S. Fish and Wildlife Service

Alternate and/or contributing members who participated include:

- Don Gross, Arizona Department of Water Resources
- Brian Westfall, Keller-Bliesner Engineering (consultant for the Navajo Nation)
- Michael Foley, Navajo Nation
- Larry Tamashiro, Southern Nevada Water Authority
- Janet Bair, U.S. Fish and Wildlife Service
- Drew Beckwith, Western Resource Advocates

Members added in November-December 2010 include:

- Marc Waage, Denver Water
- Carole Klopatek, Fort McDowell Yavapai Nation
- Charles Vaughn, Hualapai Tribal Nation
- Darryl Vigil, Jicarilla Apache Nation

Appendix C2
Colorado Water Demand
Scenario Quantification

Appendix C2 ─ Colorado Water Demand Scenario Quantification

1.0 Introduction

This appendix summarizes the data sources used in scenario quantification for Colorado River demand[1] for the state of Colorado and presents the results of quantification. As presented in figure C2-1, Colorado is divided into a number of planning areas that align with river basins including the Colorado River and its tributaries (Yampa, White, Gunnison, Dolores, and San Juan Rivers) as well as the South Platte and Arkansas basins that are served by Colorado River water. Data collection and development were completed at the planning area level.

The following sections present background information that summarizes the state's planning areas as well as data sources used to quantify demand scenarios by category. Following the background section, results of demand scenario quantification are presented. The results section is broken out into a Colorado Study Area summary, followed by Colorado River demand by geography and finally by category.

2.0 Background

The Colorado Water Conservation Board (CWCB) is responsible for state-level water resource planning in Colorado. The CWCB has led numerous planning studies under the *Statewide Water Supply Initiative* (SWSI; CWCB, 2010a), leading to a number of available water supply planning reports. The SWSI process includes significant public and agency input for Colorado's water resource planning.

The CWCB coordinated Colorado's efforts to provide information for scenario quantification. These efforts largely relied on information previously generated through the SWSI. However, new assumptions and/or data development were required where the assumptions of the Colorado River Basin Water Supply and Demand Study (Study) deviated from the SWSI process.

2.1 Data Sources for Quantification

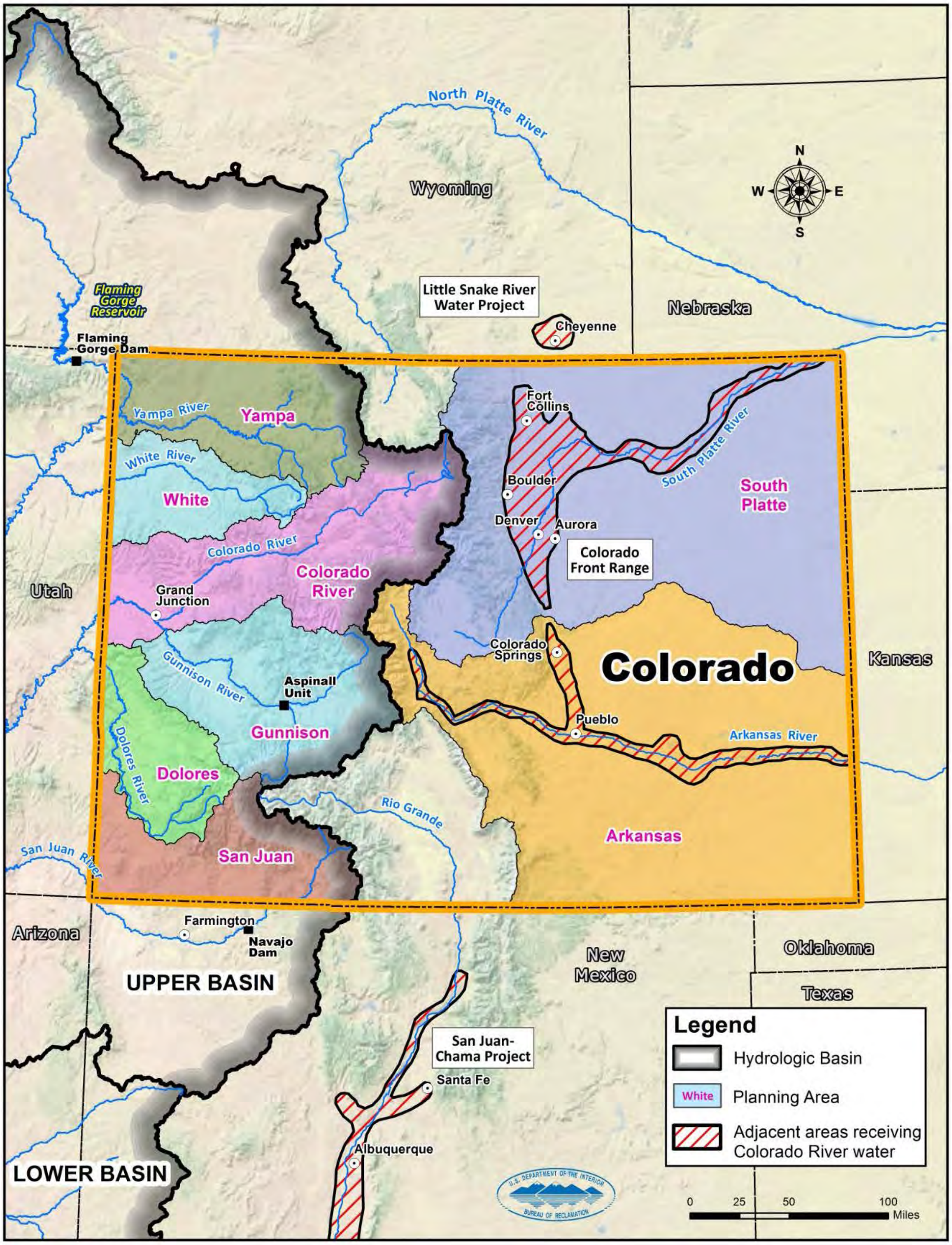
This section discusses data sources for demand quantification by use category. Some category projections were based on relevant parameter data, while other category projections were developed directly as water demand. Sources include state, regional, and national agency reports.

- Agricultural Demand: Irrigated acreage estimates were derived from SWSI table 4-10 (CWCB, 2010a). The SWSI contemplated significant future transfers of agricultural lands and water rights to meet future demands. However, for the purposes of the Study, it was assumed that agricultural to municipal and industrial (M&I) transfers were only associated with physical land transfers due to urbanization, and not associated with additional dry-up outside urban corridors. This would allow increased M&I transfers to be considered as an option and strategy to meet supply and demand imbalances.

---

[1] Colorado River demand as computed by Study Area demand minus other supplies.

FIGURE C2-1
Colorado River Hydrologic Basin and Export Service Areas in Colorado



- **M&I:** Population and per capita water use values were derived from the SWSI process. Population projection values for the Study scenarios were derived from the “low,” “medium,” and “high” values associated with the SWSI (table 4-1) and were interpolated or projected as necessary to reflect the dates reported in the Study (for example, SWSI data from 2035 and 2050 were interpolated to arrive at 2060 data for the Study). Per capita water use values were derived from “passive” and currently planned “active” conservation. Representatives from the Colorado River Water Conservation District and the Front Range Water Council reviewed the SWSI “passive” numbers in detail and concluded that the values include active measures. SWSI gallons per capita per day numbers were not used directly; the values used were provided through personal communication with the referenced entities and CWCB (CWCB, 2012).
- **Energy:** Energy demands were derived from SWSI table 4-8, with additional demands from Appendix F of the CWCB report, *2050 M&I Water User Projections* (CWCB, 2010b).
- **Minerals:** Demand for mineral production was derived from Upper Colorado River Commission Schedule of Colorado River demands from 2007. Water demand for mineral production was inadvertently excluded from the 2010 SWSI process.
- **Fish, Wildlife, and Recreation:** No water demands were noted for fish, wildlife, and recreation.
- **Tribal:** For Colorado, at the request of Ute Mountain Ute and Southern Ute Indian Tribes, tribal demands were not considered separately from the demand categories noted above. As such, tribal agricultural acreage, tribal populations, etc., are included in the other category estimates.

3.0 Results of Water Demand Scenario Quantification

This section summarizes Colorado’s Colorado River water demand trends by category across the scenarios. The purpose of this section is to describe changes in demands, both temporally and geographically, parameters that influence changes in demands, and how the parameters and demands differ among scenarios.

Demands were first developed for areas that may be potentially served by Colorado River water (Study Area demands); independent of the source of supply. However, for areas outside of the hydrologic basin, a portion of the Study Area demand is satisfied from other supplies, such as the Arkansas or South Platte rivers. To develop estimates of the Colorado River water demand, the Study Area demand was reduced by estimates of available supply from other sources. This appendix focuses on Colorado River demands, but includes discussion of the Study Area parameters that led to these demands.

The following sections summarize the results of demand scenario quantification, presenting Study Area demand and Colorado River water demand in Colorado, the Colorado River demand for the state and individual planning areas across the six scenarios, and the Colorado River water demand by category across the six scenarios. Parameters and demands for all categories and all scenarios, along with references for data sources, are included.

3.1 Summary Results of Scenario Quantification

Values were developed for parameters and demands quantified for each of the scenarios. Table C2-1 presents summary results for the demand scenarios considered in the Study. The table presents agricultural and M&I demand parameters for Colorado's Study Area, distinguishing the scenarios and the resulting Colorado River demands by category.

Colorado estimates that slightly fewer than 6 million people will be in Colorado's Study Area by 2015. This number is expected to increase to about 9 to 11 million by 2060. The greatest population growth is associated with the Rapid Growth (C1 and C2) scenarios and Enhanced Environment (D2). The Slow Growth (B) scenario has the lowest population growth of the scenarios (9.4 million by 2060), but still represents a growth of nearly 66 percent over 2015 estimates.

The growing municipal population, however, will continue to be more efficient in its per capita water use than today. Per capita water use, considering passive and active, or existing conservation levels, is expected to be 9 to 22 percent less in 2060 than in 2015. Although usage rates vary across Colorado's planning areas, per capita reductions are assumed to be consistent across the planning areas.

Irrigated acreage is projected to continue to decrease through 2060 under all scenarios. Under the Rapid Growth (C1 and C2) scenarios, projected irrigated acreage is reduced by about 420,000 acres. Irrigated acreage is reduced by 150,000 acres in the Enhanced Environment (D1) scenario, with reductions of about 40,000 acres for the Current Projected (A), Slow Growth (B), and Enhanced Environment (D2) scenarios. These reductions in irrigated acreage are offset to some extent by increases in water delivery per acre as a result of more intense cultivation or full irrigation of remaining acreage, resulting in moderate decreases in demand for all scenarios but the Enhanced Environment (D2) scenario, in which demand increases by about 4 percent.

Water demands for energy and mineral categories are projected to increase under all scenarios. The growing need for energy sources (coal, solar, and oil shale) is projected to increase water demands. The largest increases in water demand for energy are anticipated in the Colorado River and White basins. Water needs for mineral extraction are projected to increase similarly in all planning areas except for the Front Range planning areas (South Platte and Arkansas), where water demands for mineral extraction are not identified, and the Dolores basin, where demands are small.

For Colorado, tribal demands are embedded in other categories and not represented under the tribal category.

Figure C2-2 presents demands across the scenarios in three panels as follows: 1) Study Area demand with other supplies and Colorado River demand[2] identified, 2) Colorado River demand, and 3) change in Colorado River demand by demand category.

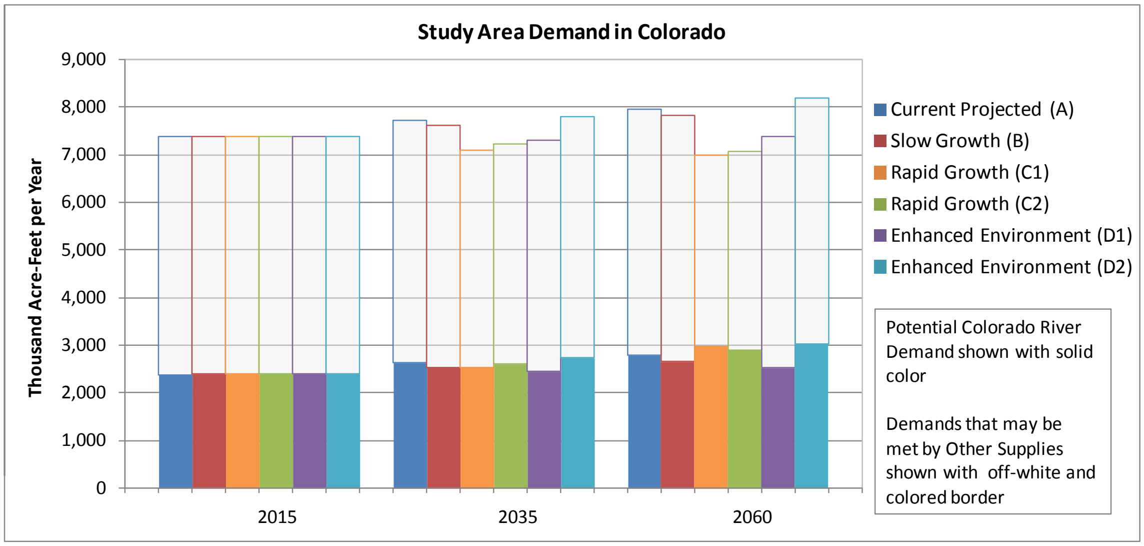
[2] Losses due to reservoir evaporation are not part of this total.

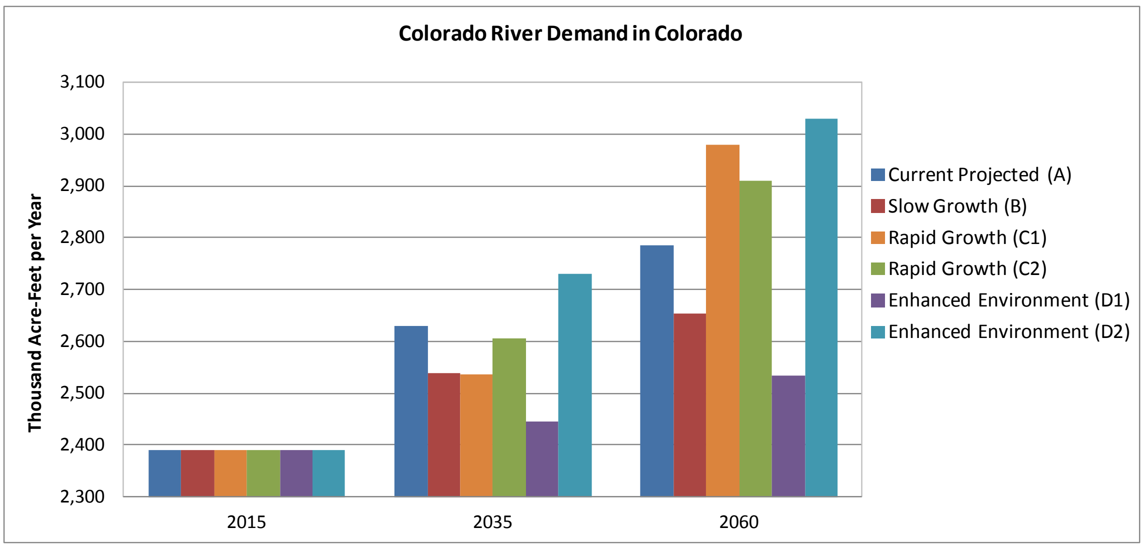
TABLE C2-1
Summary Results of Colorado Water Demand Scenario Quantification by 2060

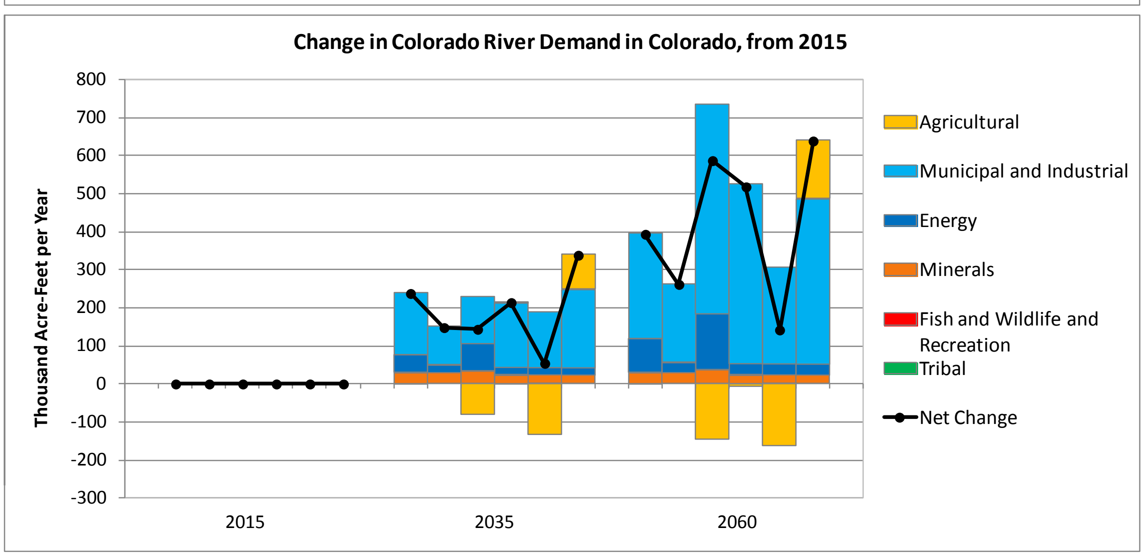
Key Study Area Demand Scenario Parameters							
	2015 [1]	2060 Scenario Parameters					
		A	B	C1	C2	D1	D2
Population (millions)	5.7	9.9	9.4	11.1	11.1	9.9	11.1
Change in per capita water usage (%), from 2015	—	-9%	-9%	-9%	-20%	-22%	-20%
Irrigated acreage (millions of acres)	2.17	2.13	2.13	1.75	1.75	2.02	2.13
Change in per acre water delivery (%), from 2015	—	+0%	+0%	+2%	+12%	-1%	+8%
Study Area Demand (thousand acre-feet [kaf])							
	2015 [1]	2060 Scenario Demands					
		A	B	C1	C2	D1	D2
Ag demand	6,132	5,991	5,991	4,775	5,252	5,767	6,367
M&I demand	1,139	1,701	1,630	1,891	1,637	1,429	1,637
Energy demand	76	195	135	255	135	128	135
Minerals demand	32	60	60	66	54	54	54
FWR demand	0	0	0	0	0	0	0
Tribal demand[2]	0	0	0	0	0	0	0
Total Study Area Demand[3]	**7,379**	**7,947**	**7,816**	**6,987**	**7,079**	**7,378**	**8,193**
Colorado River Demand (kaf)							
	2015 [1]	2060 Scenario Demands					
		A	B	C1	C2	D1	D2
Ag demand	1,875	1,875	1,875	1,728	1,867	1,711	2,029
M&I demand	455	732	661	1,007	931	711	890
Energy demand	30	118	58	178	58	58	58
Minerals demand	32	60	60	66	54	54	54
FWR demand	0	0	0	0	0	0	0
Tribal demand[2]	0	0	0	0	0	0	0
Total Colorado River Demand[3]	**2,391**	**2,784**	**2,653**	**2,979**	**2,910**	**2,534**	**3,030**

[1] If range across scenarios is less than 10 percent, Current Projected (A) is presented. Otherwise, range (min – max) is presented.
[2] Tribal demands are included in other demand categories.
[3] Excludes potential losses (reservoir evaporation, phreatophytes, and/or operational inefficiencies) that may be charged to state.

FIGURE C2-2
Study Area Demand, Colorado River Demand, and Change in Colorado River Demand







From panel one it can be seen that Study Area demand increases from about 7 million acre-feet (maf) in 2015 to up to 8.2 maf by 2060. The demand change across scenarios in 2060 is projected to be as low as a reduction of 0.4 maf or as high as an increase of 0.8 maf. The growth in Colorado River demand from 2015 to 2060 is projected to be as much as 0.6 maf with the Front Range, and in particular the South Platte planning area, growing by about 60 percent. About 60 percent of the Study Area demand is expected to be met by other supplies.

Panel two provides a view of the range across scenarios of Colorado River demand. Colorado River demand increases from about 2.4 maf in 2015 to between 2.5 and 3.0 maf in 2060 (or 6 to 27 percent) depending on the scenario. This difference results in a Colorado River demand range of about 0.5 maf across the scenarios in 2060, or about 20 percentage points.

Panel three shows how specific categories affect the projected change in Colorado River demand by scenario. Although the single largest component of demand is agricultural (~70 percent), most of the growth in demand is driven by increases in M&I demand and more specifically by increases in population. Of the growing categories of Colorado River demand, between 70 and 90 percent of the growth is contributed by the M&I demand category. Some portion of this increase is generally offset by decreases in agricultural demand, except under the Current Projected (A) and Slow Growth (B) scenarios, in which agricultural demand is constant, and under the Enhanced Environment (D2) scenario, in which agricultural demand increases significantly due to greater water delivery per acre. Water for energy and mineral demand make up the remaining increases in demand, with a significant increase in energy demand under the Rapid Growth (C1) scenario due to increased demand for oil shale production.

Figure C2-3 ties historical water use to the range of Colorado River demand in the quantified scenarios. The 0.5 maf range across scenarios in 2060 is easily discernible, with a relatively even spread over the range across the scenarios. In addition, it appears that the quantified scenarios track well with the peaks in historical uses that likely represent the least supply-limited conditions or actual demand.

3.2 Colorado River Water Demand by Geography

Colorado River water demand for areas served by the Colorado River is presented in figures C2-4, C2-5, and C2-6. These figures show two geographic levels: Study Area in Colorado, and individual planning areas. Demands at each geographic level are shown across the scenarios. The columns to the right show the Colorado River demand at a point in time (2015, 2035, or 2060) by relative contribution of the categories.

The change in both magnitude and percentage of Colorado River demand[3] varies considerably across the planning areas. The South Platte planning area shows the greatest magnitude and rate of overall growth in Colorado River demand from 2015 to 2060 across the scenarios, with between about 0.1 and 0.4 maf making up between 40 and 100 percent of the total growth in Colorado. This growth is primarily due to population growth, with between 70 and 90 percent of the increase in the growing sectors occurring in M&I demand. Demands for the Arkansas planning area are projected to grow by about 0.04 to about 0.14 maf, due to population growth. Demand in the Yampa planning area is projected to grow by between 0.02 and 0.04 maf, due

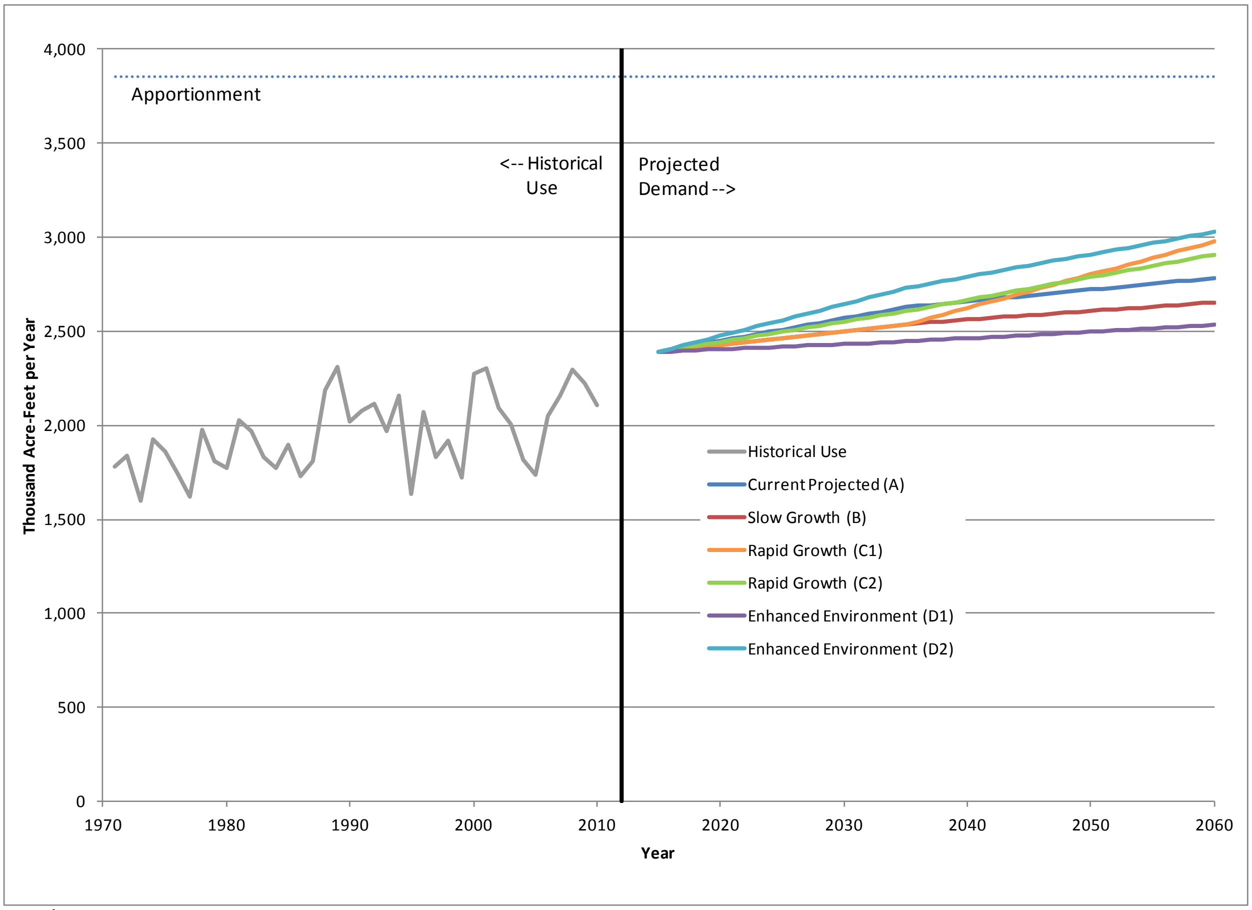
[3] Potential Colorado River demand is based on changes in parameters such as population and for the purpose of the Study is not limited by apportionment.

primarily to growth in water demand for energy. The other planning areas consistently make up the remaining growth, with greater relative contributions (more than 20 percent of total growth) from the Colorado River and White planning areas under the Current Projected (A) and Rapid Growth (C1) scenarios, respectively, due primarily to growth in demand for energy.

When demands by category are examined in figure C2-5, the mix of demand categories varies between the hydrologic basin and adjacent areas, with agricultural demand dominating the hydrologic basin and M&I demand at 50 percent or greater in the two adjacent planning areas.

Figure C2-6 shows the change in Colorado River demand by category from 2015 across the scenarios. The mix of demand categories across the planning areas varies considerably, with change in demand in the South Platte and Arkansas dominated by M&I and a range of increases and significant decreases in agricultural demand varying by basin and scenario.

FIGURE C2-3
Historical Use and Future Projected Demand Excluding Reservoir Evaporation[1]



[1]Reservoir evaporation on the order of 430 thousand acre-feet is not included in this plot.

FIGURE C2-4
Colorado River Demand in Colorado

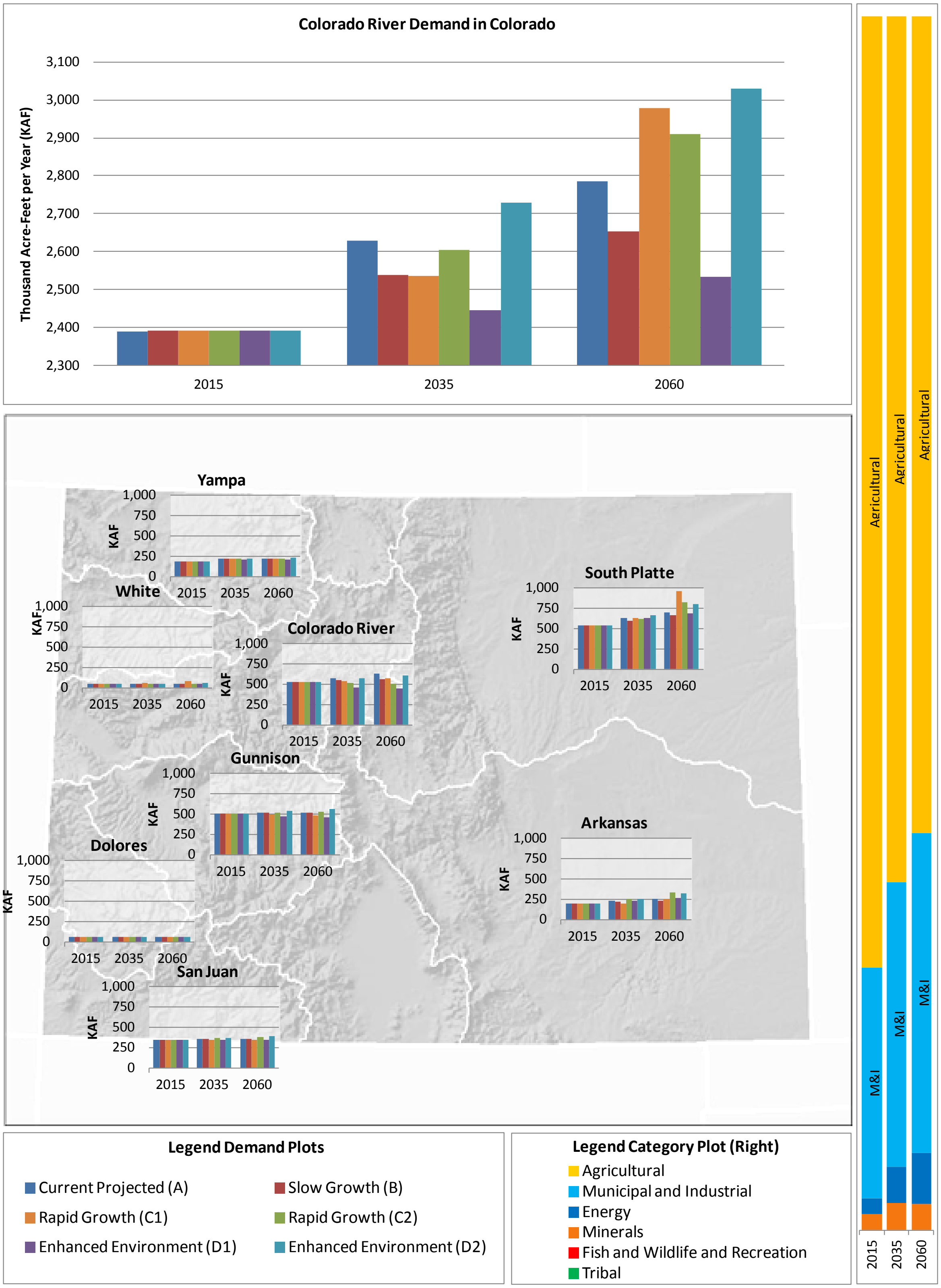


FIGURE C2-5
Colorado River Demand by Category

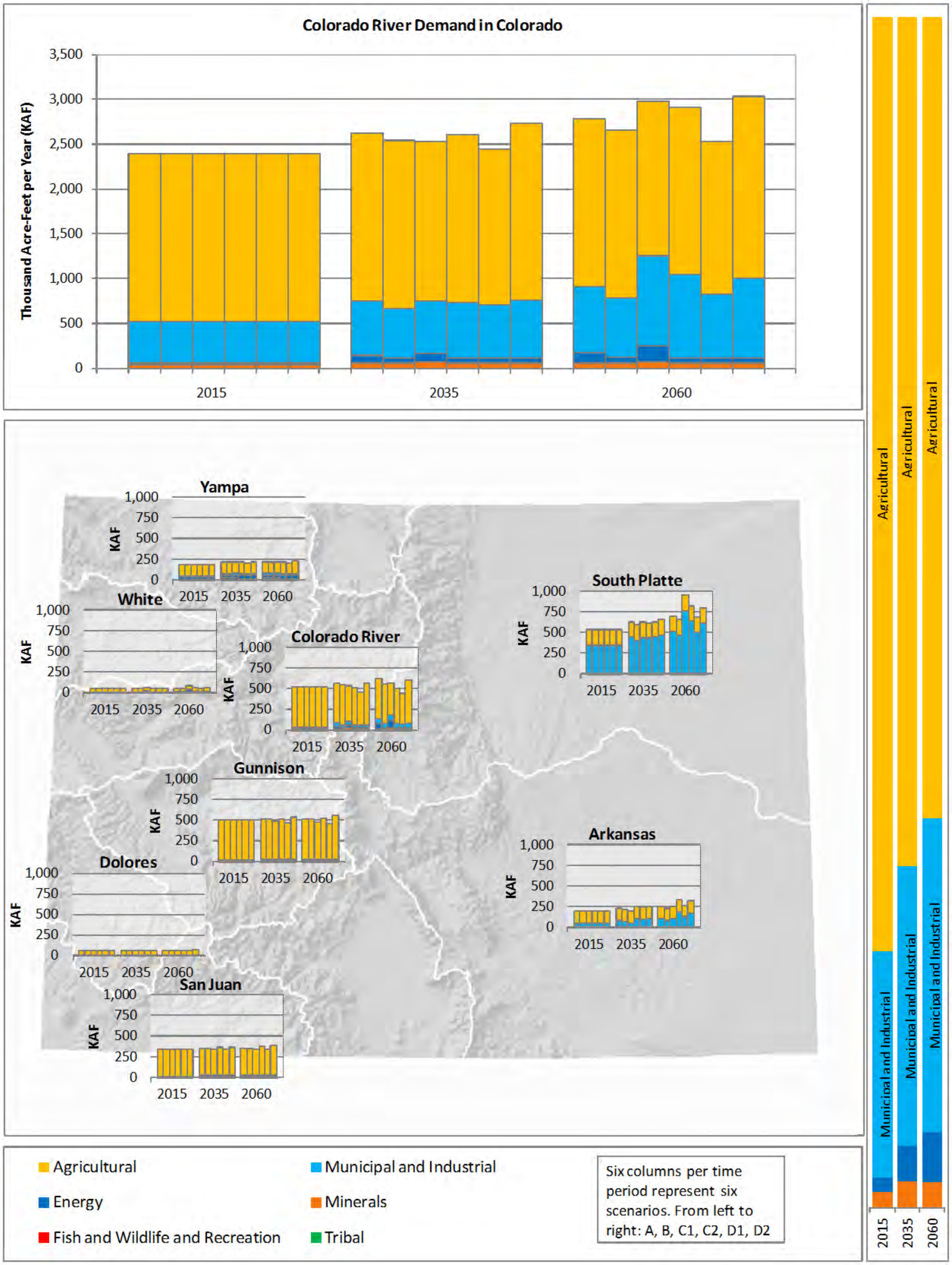
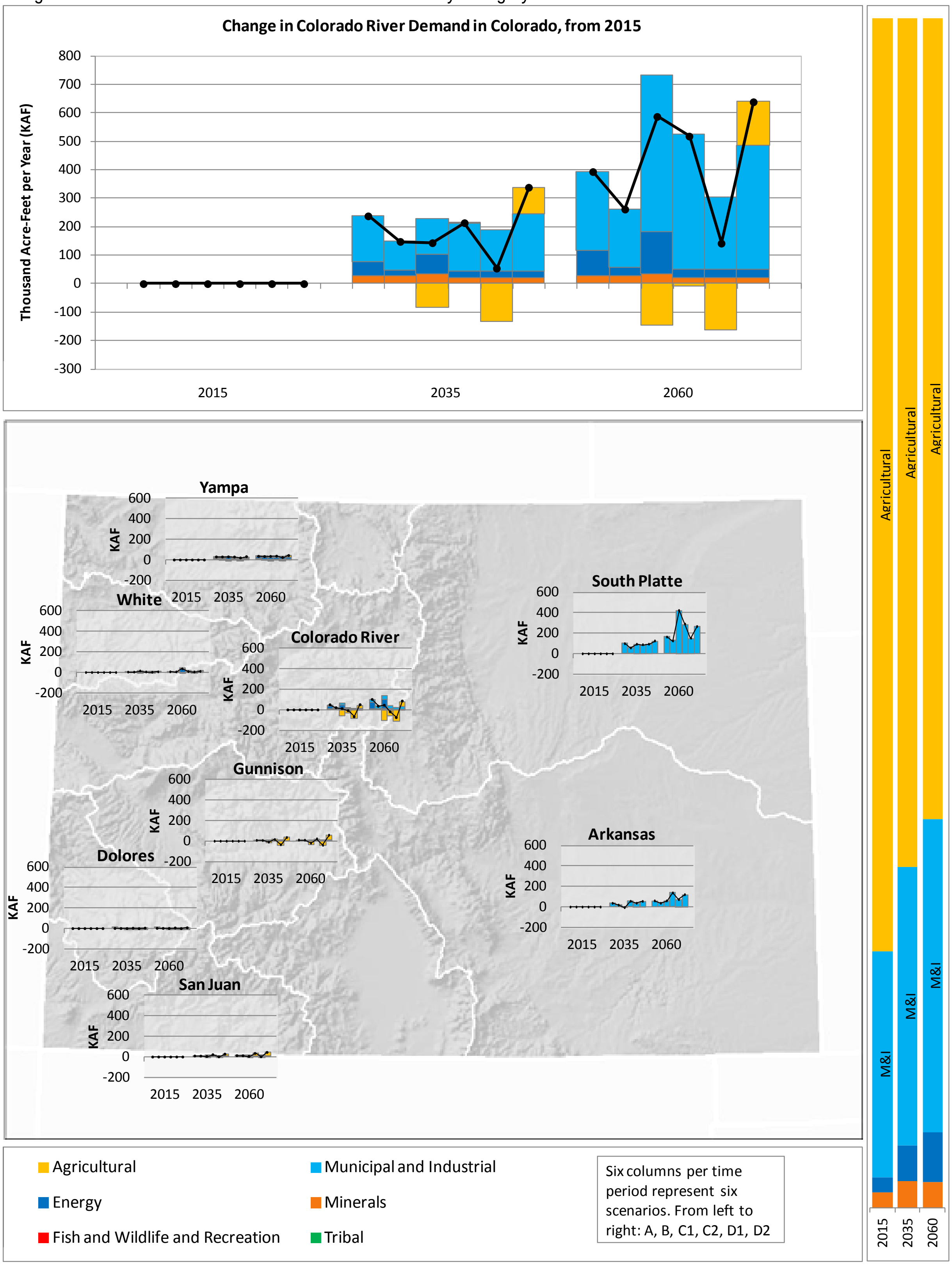


FIGURE C2-6
Change in Colorado River Demand in Colorado from 2015 by Category



3.3 Colorado River Demand by Category

3.3.1 Agriculture

Agricultural water demand is driven by irrigated acreage and water delivery per acre. Water delivery per acre is the amount of water diverted per irrigated acre. Components of this use include transmission and delivery losses (surface evaporation, riparian demand, and seepage), and on-farm losses that are made up of evaporation, crop irrigation requirements, and tail water (return). Each of these factors will vary by location (precipitation, growing season, etc.), irrigation method, and crop type.

Colorado River Simulation System (CRSS) does not represent smaller tributaries in Colorado. Inflow nodes are only included for the Mainstem Colorado, Gunnison, Yampa, San Juan, and White Rivers. Demands upstream of these inflow nodes are aggregated and represented at those same locations. A significant portion of the aggregated irrigation demands divert from the smaller tributaries and are unable to receive a full water supply during the irrigation seasons, due to either physical flow limitations or the need to bypass water to satisfy downstream senior demands. Because of CRSS limitations, Colorado demands represent supply-limited conditions instead of full irrigation demands.

Figure C2-7 presents the following by scenario in 2015, 2035, and 2060:

- Agricultural demand for Colorado River water
- Agricultural demand for Colorado River water by planning area
- Agricultural demand as a portion of Colorado River water demand (right hand side of graph)

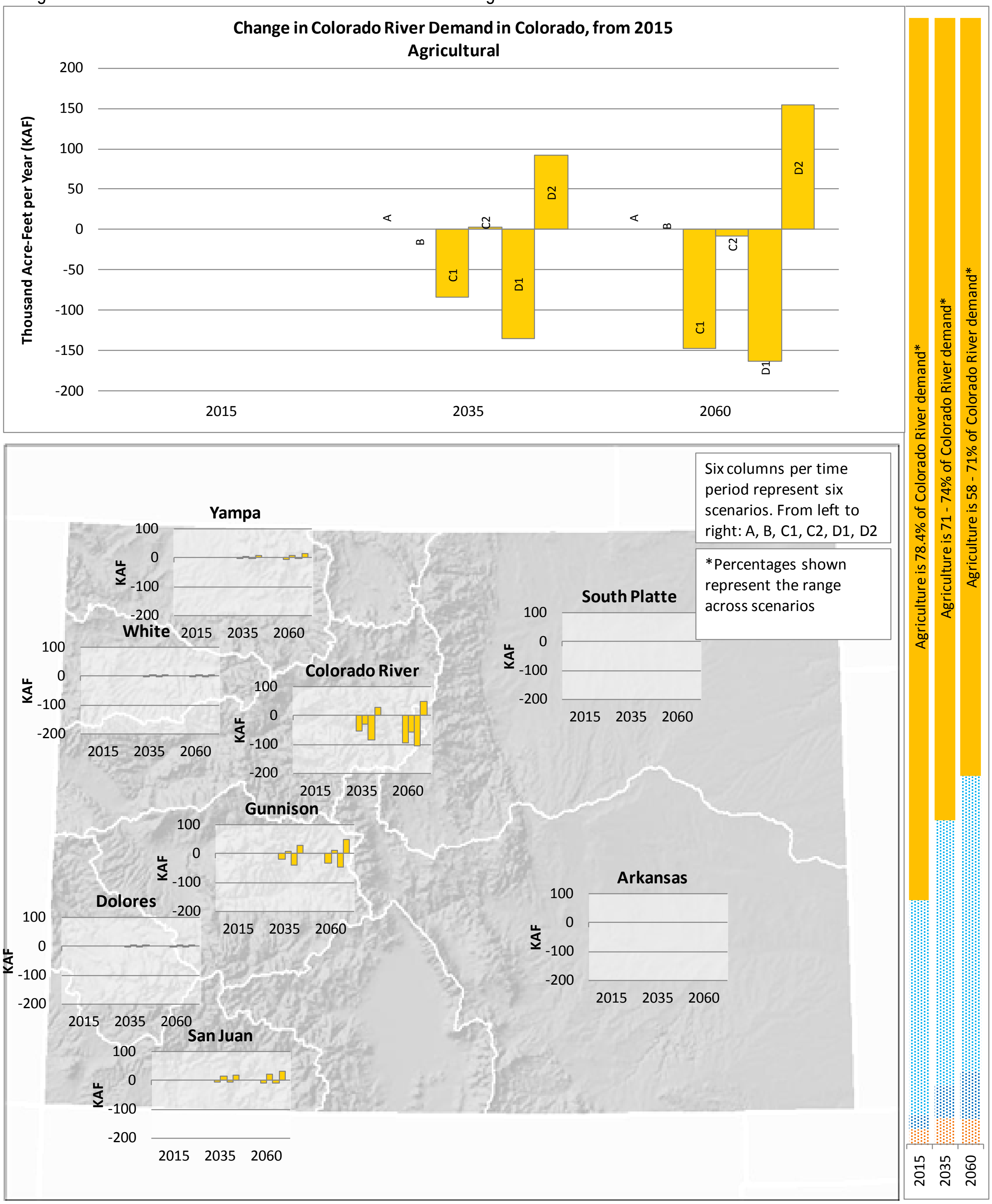
As can be seen from figure C2-7, agricultural water demand is the largest component of Colorado River demand in Colorado, dropping from about 78 percent in 2015 to between 58 and 71 percent of Colorado River demand in 2060, depending on which scenario is considered. This drop results from both a decrease in agricultural water demand and an increase in other categories of demand.

Colorado River demand for agricultural use decreases over time from 2015 to 2060 in the Rapid Growth (C1 and C2) and Enhanced Environment (D1) scenarios and increases in the Enhanced Environment (D2) scenario. The decreases are entirely due to a loss of irrigated acreage. The increase in demand in the Enhanced Environment (D2) scenario because decreases in irrigated acreage are overcome by increases in water delivery per acre due to more intensive agricultural production on these lands.

In examining the planning areas, agricultural demand consistently decreases in the Rapid Growth (C1) and Enhanced Environment (D1) scenarios and increases in the Enhanced Environment (D2) scenario, with variability from planning area to planning area in Rapid Growth (C2) scenario. The largest decrease in demand occurs in the Colorado River planning area.

A strong driver for loss of agricultural acreage is urbanization, leading to physical loss of acreage and market pressure for transfer of water rights. Increases in water delivery per acre are due to better delivery mechanisms or storage, allowing for more use of water on the same acreage in a given growing season.

FIGURE C2-7
Change in Colorado River Demand in Colorado from 2015 for Agriculture



Municipal and Industrial

M&I water demand can be estimated from population and M&I per capita water use, with the addition of self-served industrial (SSI) demand. M&I per capita water use is a measure of the amount of water produced or diverted per person in a given municipality. Because this measure examines all water produced by a given municipality, it often includes industrial, commercial, and institutional demand as well as residential demand. A number of factors may influence the M&I per capita water use of a given community, including the amount of industrial demand, climate, number of institutional facilities, and number of visitors.

SSI users are industries located in a given area that have their own water supply systems and are therefore not directly related to local measures of population and M&I per capita water use.

Figure C2-8 presents the following by scenario in 2015, 2035, and 2060:

- M&I demand for Colorado River water in the Study Area
- M&I demand for Colorado River water in individual planning areas
- M&I demand as a portion of Colorado River water demand (right hand side of graph)

As can be seen from figure C2-8, M&I water demand is the second largest component of Colorado River demand, increasing from about 19 percent in 2015 to between 25 and 34 percent of Colorado River demand in 2060, depending on which scenario is considered.

Colorado River demand for M&I use increases over time from 2015 to 2060 across all scenarios. The increase is primarily due to population increase, as M&I per capita water use decreases over time across all scenarios and SSI demand nominally increases or decreases.

In examining the planning areas, between 60 and 75 percent of the increase in M&I demand for Colorado River water from 2015 to 2060 over time is due to population increase in the South Platte across all scenarios. The remaining increase in demand is primarily from M&I demand in the Arkansas, with some increase in the Colorado River planning area.

Increases in population are somewhat tempered by decreases in M&I per capita water use. Per capita water use decreases in all scenarios, with reductions ranging from 9 to 22 percent by 2060.

3.3.2 Energy

Water demand for energy can be estimated through known plans for new power plants or through applying a per capita energy water use factor. Power facilities often serve areas remote from their locations and therefore potentially represent exports or imports of energy and water from the Study Area to meet these distributed needs.

Figure C2-9 presents the following by scenario in 2015, 2035, and 2060:

- Energy demand for Colorado River water
- Energy demand for Colorado River water by planning area
- Energy demand as a portion of total Colorado River water demand (right hand side of graph)

As can be seen from figure C2-9, energy water demand is a small fraction of Colorado River demand, increasing from about 1.3 percent of in 2015 to between 2 and 6 percent of Colorado River demand in 2060, depending on which scenario is considered.

FIGURE C2-8
Change in Colorado River Demand in Colorado from 2015 for M&I

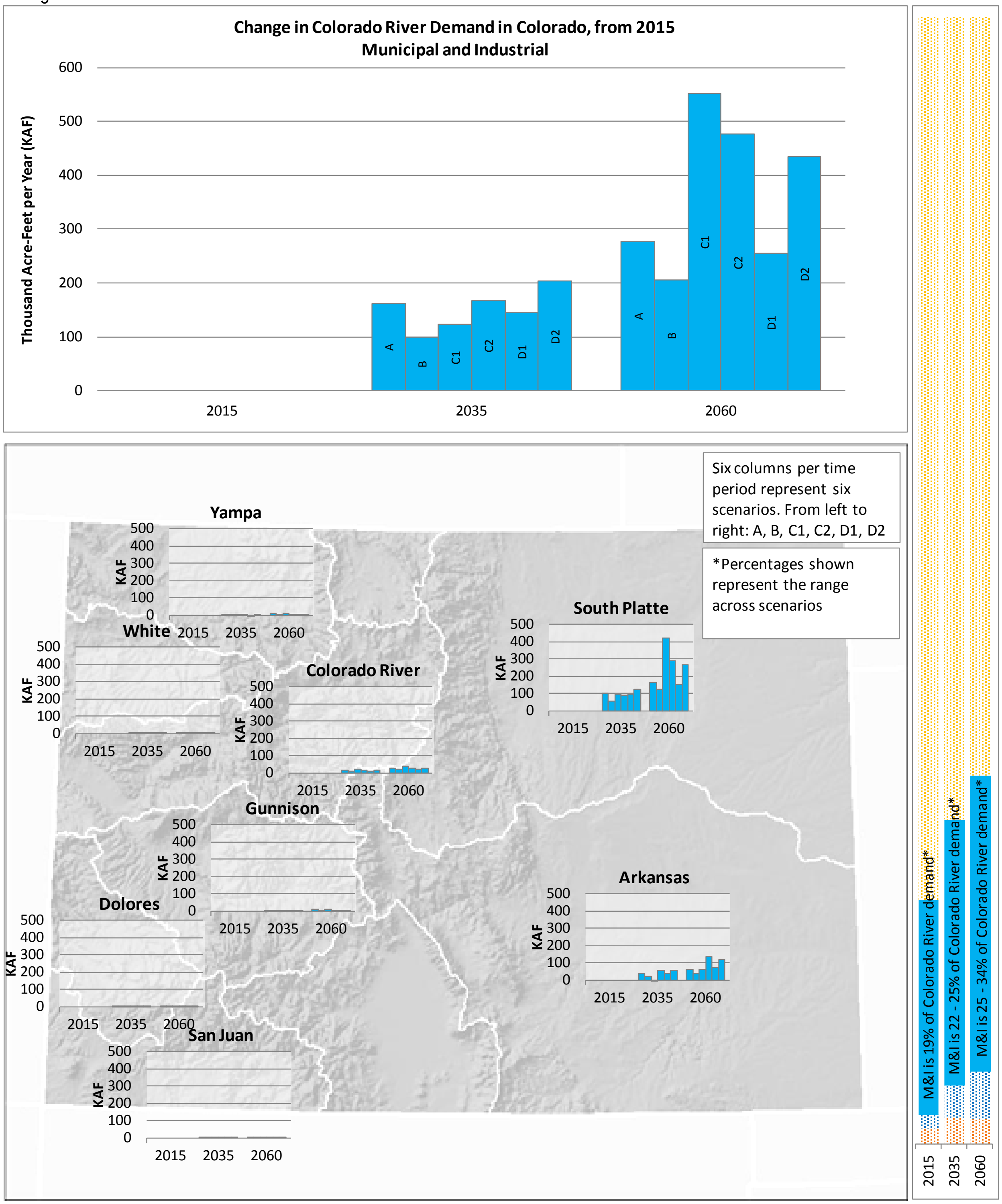
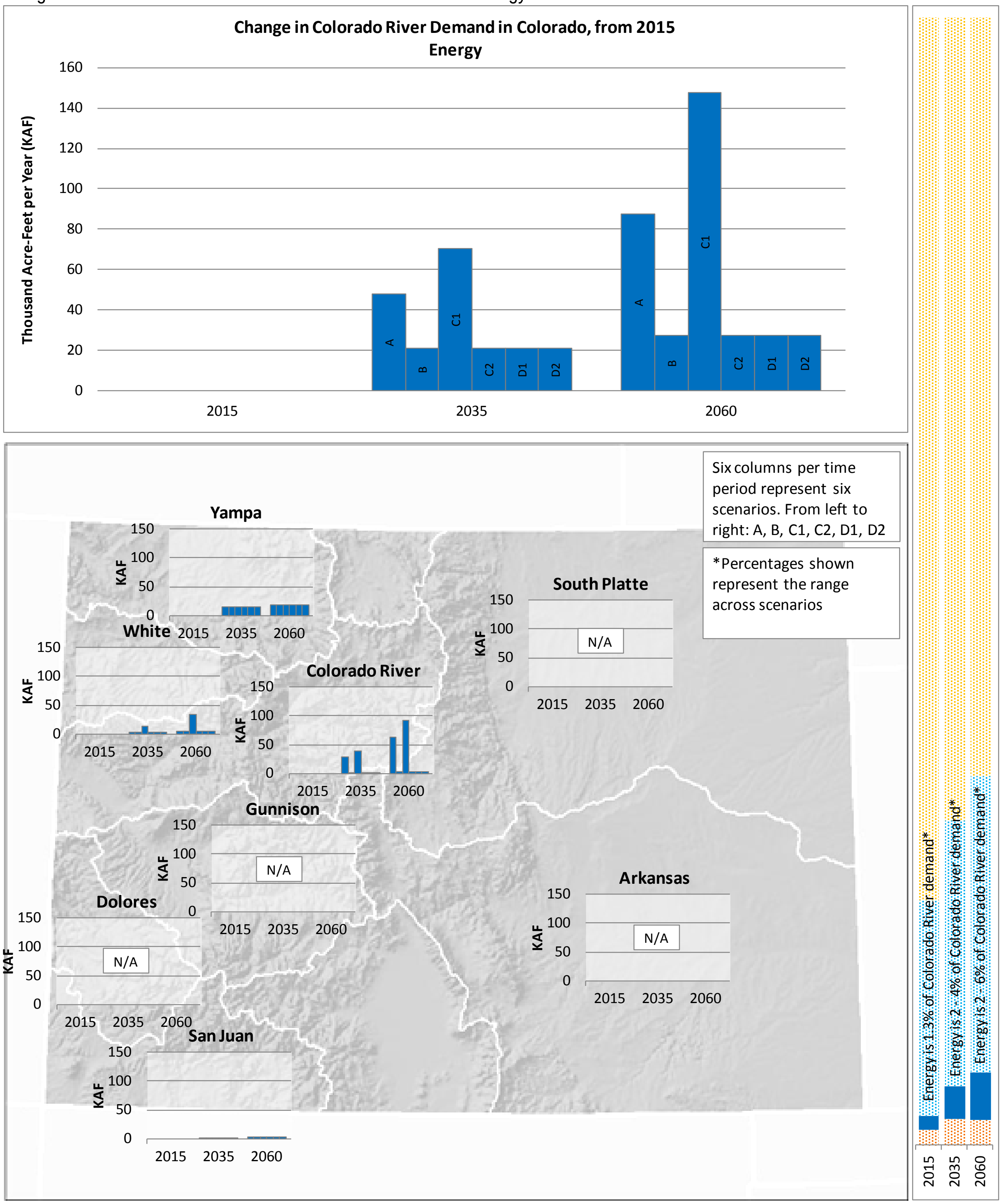


FIGURE C2-9
Change in Colorado River Demand in Colorado from 2015 for Energy



Energy demand for Colorado River water increases over time from 2015 to 2060 across all scenarios, with notable increases for the Current Projected (A) and Rapid Growth (C1) scenarios primarily due to oil shale production.

Energy demands are shown in the Yampa, White, San Juan, and Colorado River planning areas. Consistent increases occur in the Yampa planning area across all scenarios. The White planning area shows significant increases in energy demand in the Rapid Growth (C1) scenario, with nominal increases in the remaining scenarios. The San Juan planning area shows a consistent increase in energy demand across the scenarios. The Colorado River planning area shows significant increases in energy demand in the Current Projected (A) and Rapid Growth (C1) scenarios, with nominal increases in the remaining scenarios.

3.3.3 Minerals Extraction

Water demand for mineral production can be estimated through existing uses and known plans for extraction in the Study Area. Water demand for mineral production can vary significantly based on market prices for a given product.

Figure C2-10 presents the following by scenario in 2015, 2035, and 2060:

- Mineral production demand for Colorado River water
- Individual planning area mineral production demand for Colorado River water
- Minerals demand as a portion of Colorado River demand (right hand side of graph)

As can be seen from figure C2-10, minerals water demand is a small fraction of Colorado River demand, increasing from about 1.3 percent in 2015 to about 2 percent of Colorado River demand in 2060, depending on which scenario is considered.

Minerals demand for Colorado River water increases over time from 2015 to 2060 across all scenarios.

Demand for Colorado River water for minerals production is present in all of the planning areas in the hydrologic basin to varying degrees. The Yampa and Colorado River planning areas make up about 33 percent of the increase in demand each, with the Gunnison and San Juan planning areas making up about 16 percent of the increase each. Demand in the Dolores planning area is small and constant.

3.3.4 Fish, Wildlife, and Recreation

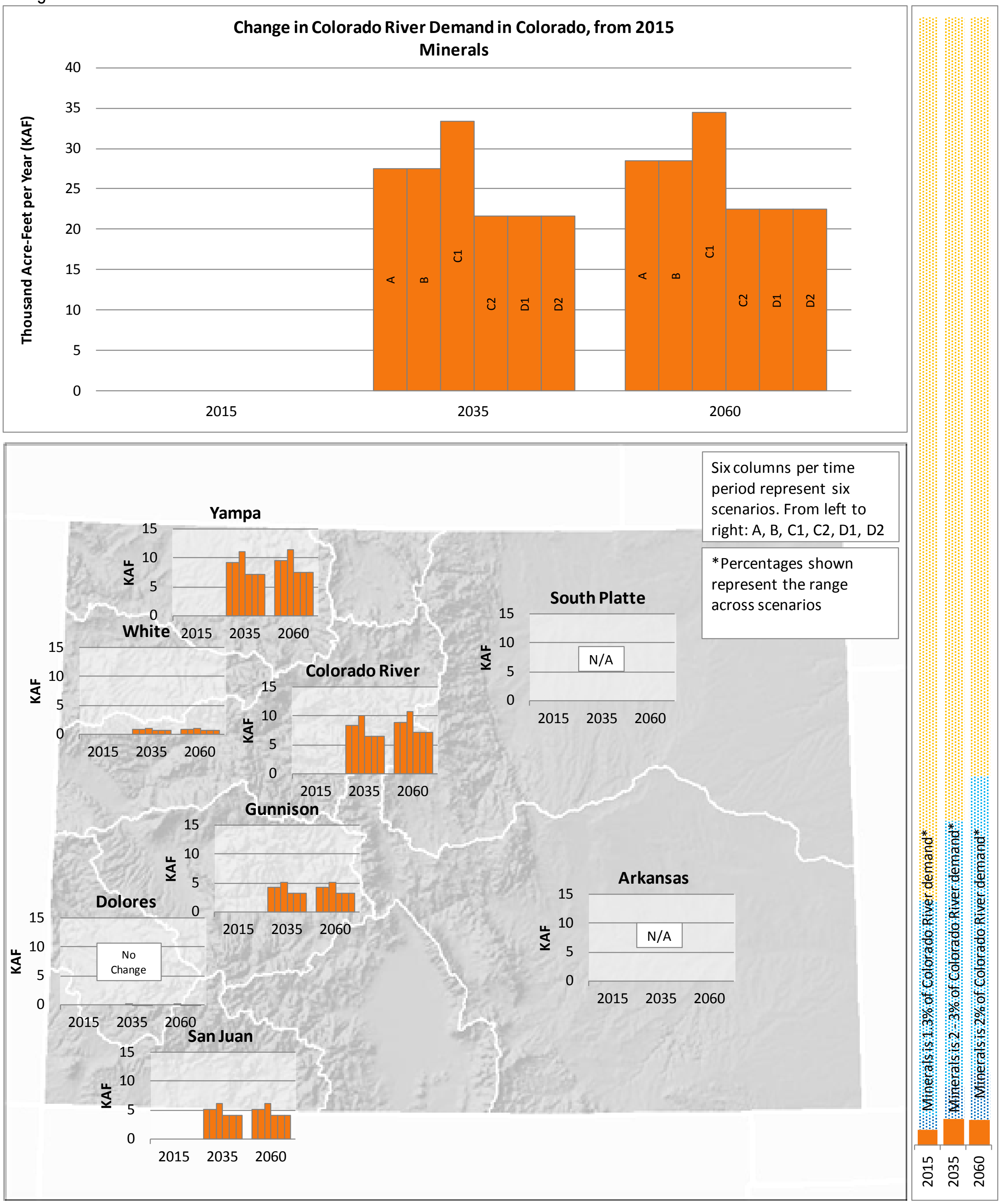
There are no consumptive fish, wildlife, and recreation demands on Colorado River water in Colorado.

3.3.5 Tribal

Tribal demands are represented as components of the other categories previously presented. The tribal reserved water rights are the senior rights in the San Juan basin in Colorado; therefore, in times when full basin demands cannot be met, the first water diverted in the basin is essentially for tribal water right diversions. The category totals in tables C2-2 to C2-5 include Southern Ute Indian Tribe and Ute Mountain Ute Indian Tribe demands.

For additional information on tribal demands, see appendix C9.

FIGURE C2-10
Change in Colorado River Demand in Colorado from 2015 for Minerals



3.4 Summary Tables of Parameters and Demands by Category

Tables C2-2 to C2-7 present the specific parameter data collected by planning area. Each table is a complete set of data for a given scenario. These data were used to develop Study Area demands and subsequently Colorado River demands once other supplies were considered. These tables provide the specific information used in the creation of the summary and category plots previously discussed and provide reference information for the data provided.

4.0 References

Colorado Water Conservation Board (CWCB). 2010a. *Statewide Water Supply Initiative*.

Colorado Water Conservation Board (CWCB). 2010b. *2050 M&I Water User Projections. Appendix F.*

Colorado Water Conservation Board (CWCB). 2012. Personal communication with Reclamation.

TABLE C2-2
Total Demand within Study Area under Current Projected (A) Scenario

LEGEND: 999 From States; 999 From State Plans; 999 Calculated; 999 From Study Team

Units are thousand acre-feet per year, unless otherwise noted

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			FRONT RANGE South Platte			FRONT RANGE Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	Notes
Agricultural	Irrigated Acreage [thousands]	270	270	270	269	269	269	93	93	93	27	27	27	220	220	220	40	40	40							918	918	918	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	6.85	6.85	6.89	6.89	6.89	4.44	4.44	4.44	10.25	10.25	10.25	3.52	3.52	3.52	3.70	3.70	3.70							5.79	5.79	5.79	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	3
	Demand (Consumptive)	**485**	**485**	**485**	**490**	**490**	**490**	**140**	**140**	**140**	**41**	**41**	**41**	**330**	**330**	**330**	**54**	**54**	**54**							**1,539**	**1,539**	**1,539**	
Municipal and Industrial (M&I)	Population [thousands]	357	558	836	121	184	244	42	65	113	10	16	28	85	130	175	36	56	75							651	1,008	1,471	5
	M&I Per Capita Use (Diversion) [gpcd]	181	173	164	173	166	157	228	219	208	228	219	208	182	174	165	182	174	165							183	176	167	6
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	7
	M&I Demand (Consumptive)	25	38	54	8	12	15	4	6	9	1	1	2	6	9	11	3	4	5							47	69	96	
	Self Served Industrial Demand (Consumptive)	3	5	5	0	1	1	7	10	10	0	0	0	0.4	0.4	0.4	0	0	0							11	16	16	8
	Demand (Consumptive)	29	43	58	9	13	16	11	16	19	1	1	2	6	9	12	3	4	5							**58**	**85**	**112**	
Energy	**Demand (Consumptive)**	**2**	**30**	**65**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**4**	**6**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**78**	**118**	9
Minerals	**Demand (Consumptive)**	**10**	**18**	**19**	**5**	**9**	**9**	**10**	**20**	**20**	**1**	**2**	**2**	**5**	**10**	**10**	**1**	**1**	**1**							**32**	**59**	**60**	10
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	11
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**575**	**626**	**503**	**512**	**515**	**186**	**215**	**221**	**44**	**48**	**51**	**343**	**352**	**356**	**58**	**59**	**60**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,762**	**1,829**	
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	810	789	428	427	426	1,255	1,237	1,215	12
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.50	3.50	3.97	3.97	3.97	3.66	3.66	3.66	2
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	3
	Demand (Diversion)																			**2,893**	**2,832**	**2,758**	**1,700**	**1,697**	**1,693**	**4,593**	**4,529**	**4,451**	4, 20
	Demand (Consumptive)																			1,112	1,089	1,061	543	542	541	**1,656**	**1,631**	**1,602**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,244	6,581	1,079	1,451	1,846	5,024	6,695	8,427	13
	M&I Per Capita Use (Diversion) [gpcd]																			170	164	154	184	176	167	173	167	157	6
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	7
	M&I Demand (Diversion)																			751	963	1,135	222	286	345	973	1,249	1,481	8
	Self Served Industrial Demand (Diversion)																			59	59	59	49	49	49	108	108	108	14
	Demand (Diversion)																			**810**	**1,022**	**1,194**	**271**	**335**	**395**	**1,081**	**1,358**	**1,589**	
	Demand (Consumptive)																			**322**	**396**	**456**	**127**	**150**	**170**	**449**	**546**	**627**	
Energy	**Demand (Diversion)**																			**36**	**47**	**59**	**10**	**15**	**18**	**46**	**62**	**78**	15
Minerals	**Demand (Diversion)**																			**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	16
Tribal	**Demand (Diversion)**																			**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	16
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,901**	**4,012**	**1,982**	**2,047**	**2,106**	**5,720**	**5,949**	**6,118**	17
Total Demand in the Study Area		**525**	**575**	**626**	**503**	**512**	**515**	**186**	**215**	**221**	**44**	**48**	**51**	**343**	**352**	**356**	**58**	**59**	**60**	**3,739**	**3,901**	**4,012**	**1,982**	**2,047**	**2,106**	**7,379**	**7,710**	**7,947**	18
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,204	3,268	3,315	1,784	1,813	1,848	4,988	5,082	5,163	
Potential Colorado River Demand		**525**	**575**	**626**	**503**	**512**	**515**	**186**	**215**	**221**	**44**	**48**	**51**	**343**	**352**	**356**	**58**	**59**	**60**	**534**	**633**	**697**	**198**	**234**	**258**	**2,391**	**2,629**	**2,784**	19, 21
Agricultural	Colorado River Demand	485	485	485	490	490	490	140	140	140	41	41	41	330	330	330	54	54	54	187	187	187	148	148	148	1,875	1,875	1,875	22
Municipal and Industrial	Colorado River Demand	29	43	58	9	13	16	11	16	19	1	1	2	6	9	12	3	4	5	347	446	510	49	86	110	455	617	732	
Energy	Colorado River Demand	2	30	65	0	0	0	25	40	42	1	4	6	2	4	5	0	0	0	0	0	0	0	0	0	30	78	118	
Minerals	Colorado River Demand	10	18	19	5	9	9	10	20	20	1	2	2	5	10	10	1	1	1	0	0	0	0	0	0	32	59	60	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes:

1) Based on Colorado Decision Support System estimates, also used in SWSI. Irrigated acreage in the Colorado River basin-estimated to remain constant (SWSI table 4-10).
2) Calculated from SWSI as headgate diversion to irrigation divided by acreage. See supporting table below.
3) System efficiency = supply-limited consumptive use divided by headgate diversions. See supporting table below.
4) Diversions in the South Platte and Arkansas include both surface water and alluvial ground water sources.
5) Population for 2015 interpolated between SWSI 2008 and SWSI 2035 estimates. Population for 2035 from SWSI. Population for 2060 extrapolated based SWSI increases between 2035 and 2050 medium estimates (SWSI table 4-1).
6) Per capita water withdrawal demands based on SWSI 2010 estimates, reduced by 10 percent in 2060 based on description in current trend analysis (table 4-3).
7) Consumptive use efficiency factor from CWCB CU&L Report.
8) Industrial based on SWSI table 4-8. Includes "Large Industry" and "Snowmaking" categories. Assumed to be 100 percent consumptive.
9) Energy demands based on SWSI table 4-8. Includes "Energy Development" and Thermoelectric" categories through 2050. An additional 60,000 acre-feet (af) is estimated to occur in the Colorado River basin based on the CWCB 2050 M&I Water User Projections July 2010 Report, Appendix F Medium projection. Assumed to be 100 percent consumptive.
10) Mineral uses were not included in SWSI. Uses are from the UCRS Schedule.
11) Tribal demands are included in the San Juan basin demands under the specific demand category. Their demands are estimated using the same parameters for Ag and M&I.
12) Per the Current Trend Storyline, agricultural use in the Arkansas and South Platte basins stay relatively constant. 2060 numbers reflect reduction based on table 4-11 low "decrease in acreage due to Urbanization". 2035 represents 1/2 of the low decrease in acreage due to urbanization value.
13) See 5) Population estimates for the entire Arkansas Basin; and the South Platte and Metro estimates combined from SWSI. Note that the entire South Platte and Arkansas basin cannot receive Colorado River basin water.
14) Industry demands based on SWSI Large Industry demands. Note that this is appropriate because there is no mining included in the South Platte and Arkansas estimates. 2008 estimates are used for 2011. There is no change shown between 2035 and 2050, therefore 2050 estimates are used for 2060. (SWSI table 4-4). Assumed 100 percent consumptive.
15) Energy demands for the Arkansas and the South Platte represent SWSI Thermoelectric Power demands. 2008 values were used for 2011, 2050 medium level was used to estimate 2060. (SWSI table 4-6)
16) Based on SWSI estimates – no mineral, fish and wildlife, or tribal use in the Arkansas and South Platte.
17) Note that Arkansas and South Platte estimates do not include losses due to Reservoir Evaporation, estimated to be as high a as 500,000 af.
18) Calculated from the sum of Hydrologic Basin (Consumptive) Demand and Adjacent Areas (Diversion) Demand.
19) Current trans-Basin diversions based on recent averages and SWSI estimates split between basins based on average annual diversion over the 2000 to 2010 period. Future exports consider reuse of trans-Basin water. Note that essentially 100 percent of current trans-Basin water is reused within the service area – not necessarily by the original user (i.e., return flows from municipal exports may be reused by agricultural users).
20) Agricultural transfers reduce the diversion demand only by the consumptive use portion—under Colorado Water Law, the return flows must be left in the river for the downstream diverters who have historically re-diverted them.
21) As new Colorado River water is brought to the front range for municipal use, it will move towards 100 percent consumptive by the importing entity (100 percent reuse).
22) Colorado River demand in adjacent areas is distributed amongst categories according to current estimated distribution of trans-Basin diversions.

TABLE C2-3
Total Demand within Study Area under Slow Growth (B) Scenario

COLORADO

Units are thousand acre-feet per year, unless otherwise noted

LEGEND: 999 From Current Projected Data She | 999 Computed | 999 Input Parameter

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			South Platte			Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	Notes
Agricultural	Irrigated Acreage [thousands]	270	270	270	269	269	269	93	93	93	27	27	27	220	220	220	40	40	40							918	918	918	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	6.85	6.85	6.89	6.89	6.89	4.44	4.44	4.44	10.25	10.25	10.25	3.52	3.52	3.52	3.70	3.70	3.70							5.79	5.79	5.79	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	
	Demand (Consumptive)	**485**	**485**	**485**	**490**	**490**	**490**	**140**	**140**	**140**	**41**	**41**	**41**	**330**	**330**	**330**	**54**	**54**	**54**							**1,539**	**1,539**	**1,539**	
Municipal and Industrial (M&I)	Population [thousands]	357	531	748	121	169	230	42	61	86	10	15	20	85	118	159	36	51	68							651	945	1,312	3
	M&I Per Capita Use (Diversion) [gpcd]	181	173	164	173	166	157	228	219	208	228	219	208	182	174	165	182	174	165							183	176	166	4
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	
	M&I Demand (Consumptive)	25	36	48	8	11	14	4	5	7	0.9	1	2	6	8	10	3	3	4							47	65	86	
	Self Served Industrial Demand (Consumptive)	3	5	5	0.3	0.7	0.7	7	10	10	0	0	0	0.4	0.4	0.4	0	0	0							11	16	16	5
	Demand (Consumptive)	**29**	**41**	**53**	**9**	**12**	**15**	**11**	**15**	**17**	**0.9**	**1**	**2**	**6**	**8**	**11**	**3**	**3**	**4**							**58**	**81**	**102**	
Energy	**Demand (Consumptive)**	**2**	**3**	**5**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**4**	**6**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**51**	**58**	6
Minerals	**Demand (Consumptive)**	**10**	**18**	**19**	**5**	**9**	**9**	**10**	**20**	**20**	**1**	**2**	**2**	**5**	**10**	**10**	**1**	**1**	**1**							**32**	**59**	**60**	7
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	8
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	9
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**547**	**561**	**503**	**511**	**514**	**186**	**215**	**219**	**44**	**48**	**50**	**343**	**352**	**355**	**58**	**59**	**60**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,731**	**1,758**	
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	810	789	428	427	426	1,255	1,237	1,215	10
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.50	3.50	3.97	3.97	3.97	3.66	3.66	3.66	11
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	
	Demand (Diversion)																			**2,893**	**2,832**	**2,758**	**1,700**	**1,697**	**1,693**	**4,593**	**4,529**	**4,451**	
	Demand (Consumptive)																			**1,112**	**1,089**	**1,061**	**543**	**542**	**541**	**1,656**	**1,631**	**1,602**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,020	6,364	1,079	1,366	1,724	5,024	6,386	8,088	12
	M&I Per Capita Use (Diversion) [gpcd]																			170	164	154	184	176	167	173	167	157	13
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	
	M&I Demand (Diversion)																			751	922	1,098	222	269	323	974	1,191	1,420	
	Self Served Industrial Demand (Diversion)																			59	59	59	49	49	49	108	108	108	14
	Demand (Diversion)																			**810**	**981**	**1,157**	**272**	**319**	**372**	**1,082**	**1,300**	**1,529**	
	Demand (Consumptive)																			**284**	**343**	**405**	**95**	**112**	**130**	**379**	**455**	**535**	
Energy	**Demand (Diversion)**																			36	47	59	10	15	18	**46**	**62**	**78**	15
Minerals	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	17
Tribal	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	18
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,860**	**3,974**	**1,982**	**2,030**	**2,083**	**5,721**	**5,891**	**6,058**	
Total Demand in the Study Area		**525**	**547**	**561**	**503**	**511**	**514**	**186**	**215**	**219**	**44**	**48**	**50**	**343**	**352**	**355**	**58**	**59**	**60**	**3,739**	**3,860**	**3,974**	**1,982**	**2,030**	**2,083**	**7,380**	**7,621**	**7,816**	
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3,204**	**3,268**	**3,315**	**1,784**	**1,813**	**1,848**	4,988	5,082	5,163	19
Potential Colorado River Demand		**525**	**547**	**561**	**503**	**511**	**514**	**186**	**215**	**219**	**44**	**48**	**50**	**343**	**352**	**355**	**58**	**59**	**60**	**534**	**592**	**660**	**198**	**217**	**235**	**2,391**	**2,540**	**2,653**	20
Agricultural	Colorado River Demand	485	485	485	490	490	490	140	140	140	41	41	41	330	330	330	54	54	54	187	187	187	148	148	148	1,875	1,875	1,875	21
Municipal and Industrial	Colorado River Demand	29	41	53	9	12	15	11	15	17	0.9	1	2	6	8	11	3	3	4	347	405	473	50	69	87	455	555	661	
Energy	Colorado River Demand	2	3	5	0	0	0	25	40	42	1	4	6	2	4	5	0	0	0	0	0	0	0	0	0	30	51	58	
Minerals	Colorado River Demand	10	18	19	5	9	9	10	20	20	1	2	2	5	10	10	1	1	1	0	0	0	0	0	0	32	59	60	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes:

1) No changes from Current Projected.
2) No changes from Current Projected.
3) Used low population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 low estimates.
4) No changes from Current Projected.
5) No changes from Current Projected.
6) Energy demands based on SWSI table 4-8. Includes Energy Development" and Thermoelectric categories through 2050. Assumed to be 100 percent consumptive.
7) No changes from Current Projected.
8) No changes from Current Projected.
9) No changes from Current Projected.
10) No changes from Current Projected.
11) No changes from Current Projected.
12) Used low population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 low estimates.
13) No changes from Current Projected.
14) No changes from Current Projected.
15) No changes from Current Projected.
16) No changes from Current Projected.
17) No changes from Current Projected.
18) No changes from Current Projected.
19) Set to Current Trend estimates based on same trends to increase use of existing projects and non-tributary groundwater.
20) Total Adjacent Area demand less Demand that may be met by Other Supplies.
21) Agricultural Use is estimated to be same as Current Projected for Adjacent Areas. Remaining Adjacent Area use is estimated to be M&I.

TABLE C2-4
Total Demand within Study Area under Rapid Growth (C1) Scenario

COLORADO
Units are thousand acre-feet per year, unless otherwise noted

LEGEND: 999 From Current Projected Data She | 999 Computed | 999 Input Parameter

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			South Platte			Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	**Notes**
Agricultural	Irrigated Acreage [thousands]	270	240	217	269	259	251	93	91	89	27	26	26	220	216	213	40	39	39							918	871	835	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	6.85	6.85	6.89	6.89	6.89	4.44	4.44	4.44	10.25	10.25	10.25	3.52	3.52	3.52	3.70	3.70	3.70							5.79	5.75	5.71	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	
	Demand (Consumptive)	**485**	**430**	**389**	**490**	**471**	**457**	**140**	**137**	**134**	**41**	**40**	**39**	**330**	**324**	**320**	**54**	**53**	**53**							**1,539**	**1,455**	**1,392**	
Municipal and Industrial (M&I)	Population [thousands]	357	628	968	121	189	274	42	88	146	10	21	36	85	136	200	36	58	86							651	1,121	1,709	3
	M&I Per Capita Use (Diversion) [gpcd]	181	173	164	173	166	157	228	219	208	228	219	208	182	174	165	182	174	165							183	176	168	4
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	
	M&I Demand (Consumptive)	25	43	62	8	12	17	4	8	12	0.9	2	3	6	9	13	3	4	6							47	78	112	
	Self Served Industrial Demand (Consumptive)	3	5	5	0.3	0.7	0.7	7	10	10	0	0	0	0.4	0.4	0.4	0	0	0							11	16	16	5
	Demand (Consumptive)	**29**	**47**	**67**	**9**	**13**	**18**	**11**	**18**	**22**	**0.9**	**2**	**3**	**6**	**10**	**13**	**3**	**4**	**6**							**58**	**93**	**128**	
Energy	**Demand (Consumptive)**	**2**	**41**	**95**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**15**	**36**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**101**	**178**	6
Minerals	**Demand (Consumptive)**	**10**	**20**	**20**	**5**	**10**	**10**	**10**	**21**	**22**	**1**	**2**	**2**	**5**	**11**	**11**	**1**	**1**	**1**							**32**	**65**	**66**	7
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	8
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	9
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**538**	**571**	**503**	**494**	**485**	**186**	**216**	**220**	**44**	**59**	**80**	**343**	**348**	**349**	**58**	**58**	**59**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,715**	**1,764**	
		2	**30**	**65**																									
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	677	564	428	386	355	1,255	1,063	919	10
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.50	3.50	3.97	3.97	3.97	3.66	3.67	3.68	11
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	
	Demand (Diversion)																			**2,893**	**2,366**	**1,972**	**1,700**	**1,535**	**1,411**	**4,593**	**3,901**	**3,383**	
	Demand (Consumptive)																			**1,112**	**910**	**758**	**543**	**490**	**451**	**1,656**	**1,400**	**1,209**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,461	7,357	1,079	1,515	2,059	5,024	6,976	9,416	12
	M&I Per Capita Use (Diversion) [gpcd]																			170	164	154	184	176	167	173	167	157	13
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	
	M&I Demand (Diversion)																			751	1,003	1,269	222	299	385	974	1,302	1,654	
	Self Served Industrial Demand (Diversion)																			59	59	59	49	49	49	108	108	108	14
	Demand (Diversion)																			**810**	**1,062**	**1,328**	**272**	**348**	**434**	**1,082**	**1,410**	**1,763**	
	Demand (Consumptive)																			**284**	**372**	**465**	**95**	**122**	**152**	**379**	**494**	**617**	
Energy	**Demand (Diversion)**																			36	47	59	10	15	18	**46**	**62**	**78**	15
Minerals	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	17
Tribal	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	18
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,476**	**3,359**	**1,982**	**1,898**	**1,864**	**5,721**	**5,374**	**5,223**	
Total Demand in the Study Area		**525**	**538**	**571**	**503**	**494**	**485**	**186**	**216**	**220**	**44**	**59**	**80**	**343**	**348**	**349**	**58**	**58**	**59**	**3,739**	**3,476**	**3,359**	**1,982**	**1,898**	**1,864**	**7,380**	**7,088**	**6,987**	
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3,204**	**2,848**	**2,403**	**1,784**	**1,705**	**1,605**	4,988	4,553	4,009	19
Potential Colorado River Demand		**525**	**538**	**571**	**503**	**494**	**485**	**186**	**216**	**220**	**44**	**59**	**80**	**343**	**348**	**349**	**58**	**58**	**59**	**534**	**628**	**956**	**198**	**193**	**258**	**2,391**	**2,535**	**2,979**	20
Agricultural	Colorado River Demand	485	430	389	490	471	457	140	137	134	41	40	39	330	324	320	54	53	53	187	187	187	148	148	148	1,875	1,791	1,728	21
Municipal and Industrial	Colorado River Demand	29	47	67	9	13	18	11	18	22	0.9	2	3	6	10	13	3	4	6	347	441	769	50	45	110	455	579	1,007	
Energy	Colorado River Demand	2	41	95	0	0	0	25	40	42	1	15	36	2	4	5	0	0	0	0	0	0	0	0	0	30	101	178	
Minerals	Colorado River Demand	10	20	20	5	10	10	10	21	22	1	2	2	5	11	11	1	1	1	0	0	0	0	0	0	32	65	66	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes:

1) Used estimated 2050 High irrigated acreage from SWSI table 4-11 for 2060, linearly interpolated to estimate 2035.
2) No changes from Current Projected.
3) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
4) No changes from Current Projected.
5) No changes from Current Projected.
6) Energy demands based on SWSI table 4-8. Includes Energy Development and Thermoelectric categories through 2050. An additional 120,000 af is estimated to occur in the Colorado River Basin (30,000) and the White River Basin (30,000) based on the CWCB *2050 M&I Water User Projections* July 2010 report, appendix F, table 13, High Projection. Assumed to be 100 percent consumptive.
7) Mineral use not included in SWSI, assume 10 percent decrease from Current Projected in 2035 and in 2060.
8) No changes from Current Projected.
9) No changes from Current Projected.
10) Used estimated 2050 Low irrigated acreage from SWSI table 4-11 for 2060, linearly interpolated to estimate 2035.
11) No changes from Current Projected.
12) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
13) No changes from Current Projected.
14) No changes from Current Projected.
15) No changes from Current Projected.
16) No changes from Current Projected.
17) No changes from Current Projected.
18) No changes from Current Projected.
19) Demand that may be met from Other Supplies decreases based on full development of current water rights, expanded reuse of both trans-Basin and in-Basin sources, and decreases yield from agricultural transfers estimated to decrease 25 percent from current levels by 2060 in the South Platte; and 10 percent from current levels in the Arkansas.
20) Total Adjacent Area demand less Demand that may be met by Other Supplies.
21) Agricultural Use is estimated to be same as Current Projected for Adjacent Areas. Remaining Adjacent Area use is estimated to be M&I.

TABLE C2-5
Total Demand within Study Area under Rapid Growth (C2) Scenario

COLORADO

Units are thousand acre-feet per year, unless otherwise noted

LEGEND: 999 From Current Projected Data She 999 Computed 999 Input Parameter

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			South Platte			Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	**Notes**
Agricultural	Irrigated Acreage [thousands]	270	240	217	269	259	251	93	91	89	27	26	26	220	216	213	40	39	39							918	871	835	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	7.26	7.53	6.89	7.31	7.58	4.44	4.71	4.89	10.25	10.86	11.27	3.52	3.73	3.87	3.70	3.92	4.07							5.79	6.09	6.28	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	
	Demand (Consumptive)	**485**	**456**	**427**	**490**	**500**	**503**	**140**	**145**	**148**	**41**	**42**	**43**	**330**	**344**	**352**	**54**	**57**	**58**							**1,539**	**1,543**	**1,532**	
Municipal and Industrial (M&I)	Population [thousands]	357	628	968	121	189	274	42	88	146	10	21	36	85	136	200	36	58	86							651	1,121	1,709	3
	M&I Per Capita Use (Diversion) [gpcd]	181	165	145	173	158	138	228	208	182	228	208	182	182	166	146	182	166	146							183	168	148	4
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	
	M&I Demand (Consumptive)	25	41	55	8	12	15	4	7	10	0.9	2	3	6	9	11	3	4	5							47	74	99	
	Self Served Industrial Demand (Consumptive)	3	2	2	0.3	0.2	0.2	7	5	5	0	0	0	0.4	0.3	0.3	0	0	0							11	7	7	5
	Demand (Consumptive)	**29**	**43**	**57**	**9**	**12**	**15**	**11**	**12**	**15**	**0.9**	**2**	**3**	**6**	**9**	**12**	**3**	**4**	**5**							**58**	**81**	**106**	
Energy	**Demand (Consumptive)**	**2**	**3**	**5**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**4**	**6**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**51**	**58**	6
Minerals	**Demand (Consumptive)**	**10**	**16**	**17**	**5**	**8**	**8**	**10**	**18**	**18**	**1**	**2**	**2**	**5**	**9**	**9**	**1**	**0.9**	**0.9**							**32**	**53**	**54**	7
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	8
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	9
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**518**	**506**	**503**	**520**	**526**	**186**	**215**	**223**	**44**	**50**	**53**	**343**	**365**	**377**	**58**	**61**	**64**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,728**	**1,750**	
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	677	564	428	386	355	1,255	1,063	919	10
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.71	3.85	3.97	4.21	4.37	3.66	3.89	4.05	11
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	
	Demand (Diversion)																			**2,893**	**2,508**	**2,169**	**1,700**	**1,627**	**1,552**	**4,593**	**4,135**	**3,721**	
	Demand (Consumptive)																			**1,112**	**964**	**834**	**543**	**520**	**496**	**1,656**	**1,484**	**1,330**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,461	7,357	1,079	1,515	2,059	5,024	6,976	9,416	12
	M&I Per Capita Use (Diversion) [gpcd]																			170	155	136	184	168	147	173	158	138	13
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	
	M&I Demand (Diversion)																			751	948	1,121	222	285	339	974	1,233	1,460	
	Self Served Industrial Demand (Diversion)																			59	38	38	49	32	32	108	70	70	14
	Demand (Diversion)																			**810**	**987**	**1,159**	**272**	**317**	**371**	**1,082**	**1,304**	**1,530**	
	Demand (Consumptive)																			**284**	**345**	**406**	**95**	**111**	**130**	**379**	**456**	**536**	
Energy	**Demand (Diversion)**																			36	47	59	10	15	18	**46**	**62**	**78**	15
Minerals	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	17
Tribal	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	18
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,542**	**3,387**	**1,982**	**1,959**	**1,941**	**5,721**	**5,501**	**5,329**	
Total Demand in the Study Area		**525**	**518**	**506**	**503**	**520**	**526**	**186**	**215**	**223**	**44**	**50**	**53**	**343**	**365**	**377**	**58**	**61**	**64**	**3,739**	**3,542**	**3,387**	**1,982**	**1,959**	**1,941**	**7,380**	**7,229**	**7,079**	
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3,204**	**2,920**	**2,563**	**1,784**	**1,705**	**1,605**	4,988	4,624	4,169	19
Potential Colorado River Demand		**525**	**518**	**506**	**503**	**520**	**526**	**186**	**215**	**223**	**44**	**50**	**53**	**343**	**365**	**377**	**58**	**61**	**64**	**534**	**623**	**824**	**198**	**254**	**336**	**2,391**	**2,605**	**2,910**	20
Agricultural	Colorado River Demand	485	456	427	490	500	503	140	145	148	41	42	43	330	344	352	54	57	58	187	187	187	148	148	148	1,875	1,878	1,867	21
Municipal and Industrial	Colorado River Demand	29	43	57	9	12	15	11	12	15	0.9	2	3	6	9	12	3	4	5	347	436	637	50	106	188	455	623	931	
Energy	Colorado River Demand	2	3	5	0	0	0	25	40	42	1	4	6	2	4	5	0	0	0	0	0	0	0	0	0	30	51	58	
Minerals	Colorado River Demand	10	16	17	5	8	8	10	18	18	1	2	2	5	9	9	1	0.9	0.9	0	0	0	0	0	0	32	53	54	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes:

1) Used estimated 2050 High irrigated acreage from SWSI table 4-11 for 2060, linearly interpolated to estimate 2035.
2) No estimates for increased in agricultural efficiency in SWSI – used 10 percent increase by 2060.
3) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
4) Per capita use decreases 25 percent by 2060 based on SWSI table 7-4 passive plus medium active conservation.
5) Assume 35 percent decrease from Current Projected based on technological efficiencies.
6) Energy demands based on SWSI table 4-8. Includes "Energy Development" and Thermoelectric" categories through 2050. Assumed to be 100 percent consumptive.
7) Mineral use not included in SWSI, assume 10 percent decrease from Current Projected in 2035 and in 2060.
8) No changes from Current Projected.
9) No changes from Current Projected.
10) Used estimated 2050 Low irrigated acreage from SWSI table 4-11 for 2060, linearly interpolated to estimate 2035.
11) No estimates for increased in agricultural efficiency in SWSI – used 10 percent increase by 2060.
12) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
13) Per capita use decreases 25 percent by 2060 based on SWSI table 7-4 passive plus medium active conservation.
14) Assume 35 percent decrease from Current Projected based on technological efficiencies.
15) No changes from Current Projected.
16) No changes from Current Projected.
17) No changes from Current Projected.
18) No changes from Current Projected.
19) Demand that may be met from Other Supplies decreases based on full development of current water rights, expanded reuse of both trans-Basin and in-Basin sources, and decreases yield from agricultural transfers estimated to decrease 20 percent from current levels by 2060 in the South Platte; and 10 percent from current levels in the Arkansas.
20) Total Adjacent Area demand less Demand that may be met by Other Supplies.
21) Agricultural Use is estimated to be same as Current Projected for Adjacent Areas. Remaining Adjacent Area use is estimated to be M&I.

TABLE C2-6
Total Demand within Study Area under Enhanced Environment (D1) Scenario

COLORADO
Units are thousand acre-feet per year, unless otherwise noted

LEGEND: 999 From Current Projected Data She 999 Computed
999 Input Parameter

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			South Platte			Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	**Notes**
Agricultural	Irrigated Acreage [thousands]	270	224	212	269	246	243	93	92	91	27	27	26	220	216	215	40	39	39							918	843	826	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	6.85	6.85	6.89	6.89	6.89	4.44	4.44	4.44	10.25	10.25	10.25	3.52	3.52	3.52	3.70	3.70	3.70							5.79	5.71	5.69	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	
	Demand (Consumptive)	**485**	**401**	**381**	**490**	**449**	**443**	**140**	**138**	**138**	**41**	**40**	**40**	**330**	**323**	**322**	**54**	**53**	**53**							**1,539**	**1,405**	**1,376**	
Municipal and Industrial (M&I)	Population [thousands]	357	558	836	121	184	244	42	65	113	10	16	28	85	130	175	36	56	75							651	1,008	1,471	3
	M&I Per Capita Use (Diversion) [gpcd]	181	163	140	173	156	134	228	205	177	228	205	177	182	164	141	182	164	141							183	165	143	4
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	
	M&I Demand (Consumptive)	25	36	46	8	11	13	4	5	8	0.9	1	2	6	8	10	3	4	4							47	65	82	
	Self Served Industrial Demand (Consumptive)	3	2	2	0.3	0.2	0.2	7	5	5	0	0	0	0.4	0.3	0.3	0	0	0							11	7	7	5
	Demand (Consumptive)	**29**	**38**	**48**	**9**	**11**	**13**	**11**	**10**	**12**	**0.9**	**1**	**2**	**6**	**9**	**10**	**3**	**4**	**4**							**58**	**73**	**90**	
Energy	**Demand (Consumptive)**	**2**	**3**	**5**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**4**	**6**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**51**	**58**	6
Minerals	**Demand (Consumptive)**	**10**	**16**	**17**	**5**	**8**	**8**	**10**	**18**	**18**	**1**	**2**	**2**	**5**	**9**	**9**	**1**	**0.9**	**0.9**							**32**	**53**	**54**	7
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	8
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	9
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**458**	**450**	**503**	**469**	**464**	**186**	**206**	**210**	**44**	**47**	**50**	**343**	**345**	**346**	**58**	**58**	**58**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,582**	**1,577**	
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	781	773	428	426	425	1,255	1,207	1,198	10
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.50	3.50	3.97	3.97	3.97	3.66	3.66	3.67	11
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	
	Demand (Diversion)																			**2,893**	**2,730**	**2,702**	**1,700**	**1,691**	**1,689**	**4,593**	**4,421**	**4,391**	
	Demand (Consumptive)																			**1,112**	**1,050**	**1,039**	**543**	**541**	**540**	**1,656**	**1,590**	**1,579**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,244	6,581	1,079	1,451	1,846	5,024	6,695	8,427	12
	M&I Per Capita Use (Diversion) [gpcd]																			170	153	132	184	166	143	173	156	134	13
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	
	M&I Demand (Diversion)																			751	899	973	222	270	296	974	1,169	1,269	
	Self Served Industrial Demand (Diversion)																			59	38	38	49	32	32	108	70	70	14
	Demand (Diversion)																			**810**	**937**	**1,011**	**272**	**302**	**328**	**1,082**	**1,239**	**1,339**	
	Demand (Consumptive)																			**284**	**328**	**354**	**95**	**106**	**115**	**379**	**434**	**469**	
Energy	**Demand (Diversion)**																			36	45	53	10	14	17	**46**	**59**	**70**	15
Minerals	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	17
Tribal	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	18
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,712**	**3,767**	**1,982**	**2,007**	**2,033**	**5,721**	**5,719**	**5,801**	
Total Demand in the Study Area		**525**	**458**	**450**	**503**	**469**	**464**	**186**	**206**	**210**	**44**	**47**	**50**	**343**	**345**	**346**	**58**	**58**	**58**	**3,739**	**3,712**	**3,767**	**1,982**	**2,007**	**2,033**	**7,380**	**7,301**	**7,378**	
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3,204**	**3,084**	**3,081**	**1,784**	**1,772**	**1,764**	4,988	4,855	4,844	19
Potential Colorado River Demand		**525**	**458**	**450**	**503**	**469**	**464**	**186**	**206**	**210**	**44**	**47**	**50**	**343**	**345**	**346**	**58**	**58**	**58**	**534**	**628**	**686**	**198**	**236**	**270**	**2,391**	**2,446**	**2,534**	20
Agricultural	Colorado River Demand	485	401	381	490	449	443	140	138	138	41	40	40	330	323	322	54	53	53	187	187	187	148	148	148	1,875	1,740	1,711	21
Municipal and Industrial	Colorado River Demand	29	38	48	9	11	13	11	10	12	0.9	1	2	6	9	10	3	4	4	347	441	499	50	87	122	455	601	711	
Energy	Colorado River Demand	2	3	5	0	0	0	25	40	42	1	4	6	2	4	5	0	0	0	0	0	0	0	0	0	30	51	58	
Minerals	Colorado River Demand	10	16	17	5	8	8	10	18	18	1	2	2	5	9	9	1	0.9	0.9	0	0	0	0	0	0	32	53	54	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes

1) Calculated medium decrease in acreage due to urbanization using low and high acreage decreased from SWSI table 4-11 and low, high, and medium population projections from SWSI table 4-1.
2) No changes from Current Projected.
3) No changes from Current Projected.
4) Per capita use decreases 0.5 percent per year per conservation organization recommendation.
5) Assume 35 percent decrease from Current Projected based on technological efficiencies.
6) Energy demands based on SWSI table 4-8. Includes "Energy Development" and Thermoelectric" categories through 2050. Assumed to be 100 percent consumptive.
7) Mineral use not included in SWSI, assume 10 percent decrease from Current Projected in 2035 and in 2060.
8) No changes from Current Projected.
9) No changes from Current Projected.
10) Calculated medium decrease in acreage due to urbanization using low and high acreage decreased from SWSI table 4-11 and low, high, and medium population projections from SWSI table 4-1.
11) No changes from Current Projected.
12) Used medium population estimates from the SWSI table 4-1 for all basins.
13) Per capita use decreases 0.5 percent per year per conservation organization recommendation.
14) Assume 35 percent decrease from Current Projected based on technological efficiencies.
15) No changes from Current Projected.
16) No changes from Current Projected.
17) No changes from Current Projected.
18) No changes from Current Projected.
19) Demand that may be met from Other Supplies decreases based on expanded reuse of both trans-Basin and in-Basin sources, estimated to decrease 3 percent from current levels by 2060 in the South Platte; and 1 percent from current levels in the Arkansas.
20) Total Adjacent Area demand less Demand that may be met by Other Supplies.
21) Agricultural Use is estimated to be same as Current Projected for Adjacent Areas. Remaining Adjacent Area use is estimated to be M&I.

Colorado River Basin
Water Supply and Demand Study

TABLE C2-7
Total Demand within Study Area under Enhanced Environment (D2) Scenario

COLORADO
Units are thousand acre-feet per year, unless otherwise noted

LEGEND: 999 From Current Projected Data She 999 Computed 999 Input Parameter

	Planning Area	Colorado River			Gunnison			Yampa			White			San Juan			Dolores			South Platte			Arkansas			STATE TOTAL			
Hydrologic Basin	Year	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	2015	2035	2060	**Notes**
Agricultural	Irrigated Acreage [thousands]	270	270	270	269	269	269	93	93	93	27	27	27	220	220	220	40	40	40							918	918	918	1
	Per-Acre Water Delivery (Diversion) [af/ac/yr]	6.85	7.26	7.53	6.89	7.31	7.58	4.44	4.71	4.89	10.25	10.86	11.27	3.52	3.73	3.87	3.70	3.92	4.07							5.79	6.13	6.36	2
	Consumptive factor [%]	26%	26%	26%	26%	26%	26%	34%	34%	34%	15%	15%	15%	43%	43%	43%	37%	37%	37%							29%	29%	29%	
	Demand (Consumptive)	**485**	**514**	**533**	**490**	**519**	**539**	**140**	**148**	**154**	**41**	**43**	**45**	**330**	**349**	**362**	**54**	**57**	**60**							**1,539**	**1,632**	**1,693**	
Municipal and Industrial (M&I)	Population [thousands]	357	628	968	121	189	274	42	88	146	10	21	36	85	136	200	36	58	86							651	1,121	1,709	3
	M&I Per Capita Use (Diversion) [gpcd]	181	165	145	173	158	138	228	208	182	228	208	182	182	166	146	182	166	146							183	168	148	4
	Consumptive factor [%]	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%	35%							35%	35%	35%	
	M&I Demand (Consumptive)	25	41	55	8	12	15	4	7	10	0.9	2	3	6	9	11	3	4	5							47	74	99	
	Self Served Industrial Demand (Consumptive)	3	2	2	0.3	0.2	0.2	7	5	5	0	0	0	0.4	0.3	0.3	0	0	0							11	7	7	5
	Demand (Consumptive)	**29**	**43**	**57**	**9**	**12**	**15**	**11**	**12**	**15**	**0.9**	**2**	**3**	**6**	**9**	**12**	**3**	**4**	**5**							**58**	**81**	**106**	
Energy	**Demand (Consumptive)**	**2**	**3**	**5**	**0**	**0**	**0**	**25**	**40**	**42**	**1**	**4**	**6**	**2**	**4**	**5**	**0**	**0**	**0**							**30**	**51**	**58**	6
Minerals	**Demand (Consumptive)**	**10**	**16**	**17**	**5**	**8**	**8**	**10**	**18**	**18**	**1.0**	**2**	**2**	**5**	**9**	**9**	**1**	**0.9**	**0.9**							**32**	**53**	**54**	7
Fish, Wildlife, and Recreation	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	8
Tribal	**Demand (Consumptive)**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**							**0**	**0**	**0**	9
Total Hydrologic Basin	**Demand (Consumptive)**	**525**	**576**	**612**	**503**	**539**	**562**	**186**	**218**	**229**	**44**	**51**	**55**	**343**	**371**	**388**	**58**	**62**	**65**	**0**	**0**	**0**	**0**	**0**	**0**	**1,659**	**1,817**	**1,911**	
Adjacent Areas																													
Agricultural	Irrigated Acreage [thousands]																			828	810	789	428	427	426	1,255	1,237	1,215	10
	Per-Acre Water Delivery (Diversion) [af/ac/yr]																			3.50	3.57	3.67	3.97	4.06	4.17	3.66	3.74	3.85	11
	Consumptive factor [%]																			38%	38%	38%	32%	32%	32%	36%	36%	36%	
	Demand (Diversion)																			**2,893**	**2,894**	**2,896**	**1,700**	**1,734**	**1,778**	**4,593**	**4,628**	**4,674**	
	Demand (Consumptive)																			**1,112**	**1,113**	**1,114**	**543**	**554**	**568**	**1,656**	**1,667**	**1,682**	
Municipal and Industrial (M&I)	Population [thousands]																			3,945	5,461	7,357	1,079	1,515	2,059	5,024	6,976	9,416	12
	M&I Per Capita Use (Diversion) [gpcd]																			170	155	136	184	168	147	173	158	138	13
	Consumptive factor [%]																			35%	35%	35%	35%	35%	35%	35%	35%	35%	
	M&I Demand (Diversion)																			751	948	1,121	222	285	339	974	1,233	1,460	
	Self Served Industrial Demand (Diversion)																			59	38	38	49	32	32	108	70	70	14
	Demand (Diversion)																			**810**	**987**	**1,159**	**272**	**317**	**371**	**1,082**	**1,304**	**1,530**	
	Demand (Consumptive)																			**284**	**345**	**406**	**95**	**111**	**130**	**379**	**456**	**536**	
Energy	**Demand (Diversion)**																			36	47	59	10	15	18	**46**	**62**	**78**	15
Minerals	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	16
Fish, Wildlife, and Recreation	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	17
Tribal	**Demand (Diversion)**																			0	0	0	0	0	0	**0**	**0**	**0**	18
Total Adjacent Areas	Demand (Diversion)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,739**	**3,928**	**4,115**	**1,982**	**2,066**	**2,167**	**5,721**	**5,994**	**6,282**	
Total Demand in the Study Area		**525**	**576**	**612**	**503**	**539**	**562**	**186**	**218**	**229**	**44**	**51**	**55**	**343**	**371**	**388**	**58**	**62**	**65**	**3,739**	**3,928**	**4,115**	**1,982**	**2,066**	**2,167**	**7,380**	**7,811**	**8,193**	
Demand that may be met by Other Supplies		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3,204**	**3,268**	**3,315**	**1,784**	**1,813**	**1,848**	4,988	5,082	5,163	19
Potential Colorado River Demand		**525**	**576**	**612**	**503**	**539**	**562**	**186**	**218**	**229**	**44**	**51**	**55**	**343**	**371**	**388**	**58**	**62**	**65**	**534**	**659**	**800**	**198**	**253**	**319**	**2,391**	**2,730**	**3,030**	20
Agricultural	Colorado River Demand	485	514	533	490	519	539	140	148	154	41	43	45	330	349	362	54	57	60	187	187	187	148	148	148	1,875	1,967	2,029	21
Municipal and Industrial	Colorado River Demand	29	43	57	9	12	15	11	12	15	0.9	2	3	6	9	12	3	4	5	347	472	613	50	105	171	455	658	890	
Energy	Colorado River Demand	2	3	5	0	0	0	25	40	42	1	4	6	2	4	5	0	0	0	0	0	0	0	0	0	30	51	58	
Minerals	Colorado River Demand	10	16	17	5	8	8	10	18	18	1	2	2	5	9	9	1	0.9	0.9	0	0	0	0	0	0	32	53	54	
Fish, Wildlife, and Recreation	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Tribal	Colorado River Demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Notes

1) No changes from Current Projected.
2) No reference. Assume 10 percent increase from Current Projected by 2060.
3) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
4) Per capita use decreases 25 percent by 2060 based on SWSI table 7-4 passive plus medium active conservation.
5) Assume 35 percent decrease from Current Projected based on technological efficiencies.
6) Energy demands based on SWSI table 4-8. Includes "Energy Development" and Thermoelectric" categories through 2050. Assumed to be 100 percent consumptive.
7) Mineral use not included in SWSI, assume 10 percent decrease from Current Projected in 2035 and in 2060.
8) No changes from Current Projected.
9) No changes from Current Projected.
10) No changes from Current Projected.
11) No reference. Assume 5 percent increase from Current Projected by 2060.
12) Used high population estimates from the SWSI table 4-1 for all basins. 2035 and 2060 interpolated from 2015 estimates and 2050 high estimates.
13) Per capita use decreases 25percent by 2060 based on SWSI table 7-4 passive plus medium active conservation.
14) Assume 35 percent decrease from Current Projected based on technological efficiencies.
15) No changes from Current Projected.
16) No reference. Assume 10 percent decrease from Current Projected in 2035 and in 2060.
17) No changes from Current Projected.
18) No changes from Current Projected.
19) No changes from Current Projected.
20) Total Adjacent Area demand less Demand that may be met by Other Supplies.
21) Agricultural Use is estimated to be same as Current Projected for Adjacent Areas. Remaining Adjacent Area use is estimated to be M&I.

Appendix C3
New Mexico Water Demand Scenario Quantification

Appendix C3 — New Mexico Water Demand Scenario Quantification

1.0 Introduction

This appendix summarizes the data sources used in scenario quantification for Colorado River demand[1] for the state of New Mexico and presents the results of quantification. As presented in figure C3-1, New Mexico is divided into a number of planning areas that align with Colorado River Basin (Basin) tributaries (San Juan, Northwest [Little Colorado tributaries], and Southwest [Gila tributaries]), and Adjacent Areas that are served by Colorado River water. Data collection and development were completed at the planning area level.

The following sections present background information that summarizes the state's planning areas, as well as data sources used to quantify demand scenarios by category. Following the background section, results of demand scenario quantification are presented. The results section is broken out into a New Mexico Study Area summary, followed by Colorado River demand by geography, and finally by category.

2.0 Background

The New Mexico Office of the State Engineer and the New Mexico Interstate Stream Commission (NMISC) are responsible for regional and state-level water resource planning in New Mexico. As part of New Mexico's state water planning process, regional plans were developed by a number of regional planning entities. The NMISC coordinated these efforts, and once they were final, adopted the resulting regional plans.

The NMISC also coordinated the efforts to provide information for scenario quantification. These efforts largely relied on information previously generated through regional plans and demographic studies. However, new assumptions and/or data development were required where the assumptions of the Colorado River Basin Water Supply and Demand Study (Study) required information not developed as part of the regional planning effort.

2.1 Data Sources for Quantification

This section discusses data sources for demand quantification by use category. Some category projections were based on relevant parameter data, while other category projections were developed directly as water demand. Sources include state, regional, and national agency reports.

[1] Colorado River demand as computed by Study Area demand minus other supplies.

FIGURE C3-1
Colorado River Hydrologic Basin and Export Service Areas in New Mexico

- **Agricultural Demand:** Irrigated acreage, agricultural applied water use, and agricultural demand estimates were derived from the *San Juan Regional Water Plan* (San Juan Water Commission, 2003), the *Southwest New Mexico Regional Water Plan* (Daniel B. Stephens & Associates [DBSA], 2005), *Taos Regional Water Plan* (DBSA, 2008), *Middle Rio Grande Water Supply Study* (S.S. Papadopoulos and Associates, 2000), and additional information was provided by the NMISC.
- **Municipal and Industrial (M&I):** Population and per capita water use values for the San Juan, Southwest, and Taos planning areas were derived from the same regional plans as agricultural parameters, and additional information was provided by the NMISC. Additional information for Adjacent Areas was derived based on the City of Albuquerque's reported efficiency and Albuquerque population estimates prepared by the Bureau of Business and Economic Research.
- **Energy:** Energy demands were derived from personal communication with the NMISC (2011) for the San Juan planning area. Some additional energy use in the Taos and Southwest planning areas was derived from the regional plans.
- **Minerals:** Minerals demands were derived from personal communication with the NMISC (2011) for the San Juan planning area.
- **Fish, Wildlife, and Recreation:** Water demands for fish, wildlife, and recreation were derived from contracted amounts based on the San Juan Chama contract.
- **Tribal:** Tribal demands were derived from personal communication with the NMISC (2011), input from the Jicarilla Apache Nation and Navajo Nation, and San Juan Chama contract amounts.

3.0 Results of Water Demand Scenario Quantification

This section summarizes New Mexico's Colorado River water demand trends by category across the scenarios. The purpose of this section is to describe changes in demands, both temporally and geographically, parameters that influence changes in demands, and how the parameters and demands differ among scenarios.

Demands were first developed for areas that may be potentially served by Colorado River water (Study Area demands), independent of the source of supply. However, for areas outside of the hydrologic basin, a portion of the Study Area demand is satisfied from other supplies, such as the Rio Grande water and local groundwater. The communities within the Basin, including the Southwest and Northwest planning areas, also rely on non-tributary groundwater for a portion of their supply. To develop estimates of the Colorado River demand, the Study Area demand was reduced by estimates of available supply from other sources. This appendix focuses on Colorado River demands, but includes discussion of the Study Area parameters that led to these demands.

The following sections summarize the results of demand scenario quantification, presenting Study Area demand and Colorado River water demand, Colorado River demand for the state and individual planning areas across the six scenarios, and Colorado River water demand by category across the six scenarios. Parameters and demands for all categories and all scenarios, along with references for data sources, are included.

3.1 Summary Results of Scenario Quantification

Values were developed for Study Area parameters to quantify Study Area demand for each of the scenarios. Colorado River demand was calculated as Study Area demand minus other supplies. Table C3-1 presents summary results for the demand scenarios considered in the Study. The table presents agricultural and M&I demand parameters for the entire Study Area that distinguish the scenarios, the resulting Study Area demands, and finally the Colorado River demands by category. Because other supplies may vary among scenarios, trends observed in the parameters and Study Area demands may not be reflected identically in Colorado River demand trends.

New Mexico estimates that about 1.5 million people will be in New Mexico's Study Area by 2015. This number is expected to increase to about 2 to 3 million by 2060. The greatest population growth is associated with the Rapid Growth (C1 and C2) and Enhanced Environment (D2) scenarios. The Slow Growth (B) scenario has the lowest population growth of the scenarios (2 million by 2060) but still represents a growth of 37 percent over 2015 estimates.

The growing municipal population, however, will continue to be more efficient in its per capita water use than today. Per capita water use, based solely on passive or existing conservation targets, is expected to be 11 to 24 percent less in 2060 than in 2015. While usage rates vary across New Mexico's planning areas, per capita reductions are assumed to be consistent across the planning areas.

Irrigated acreage is projected to decrease slightly (2 percent or 3,000 acres) through 2060 under all scenarios. Water delivery per acre does not change in the Current Projected (A), Rapid Growth (C1), and Enhanced Environment (D1) scenarios; increases slightly (4 percent) in the Slow Growth (B) scenario; and decreases by about 15 percent in the Rapid Growth (C2) and Enhanced Environment (D2) scenarios.

Study Area demand for energy is projected to increase slightly under all scenarios due to the growing need for energy sources (coal and solar). The greatest increases in Study Area demand for energy are anticipated in the San Juan planning area, with an increase of about 1,500 acre-feet per year (afy) (4 percent).

Study Area demand for minerals is projected to remain constant through time and across all scenarios.

Study Area demand for tribal use is projected to increase across all scenarios between about 20 and 75 percent. The larger increases occur in the Rapid Growth (C1 and C2) and Enhanced Environment (D2) scenarios.

Figure C3-2 presents demands across the scenarios in three panels as follows: 1) Study Area demand with other supplies and Colorado River demand identified, 2) Colorado River demand, and 3) change in Colorado River demand by demand category.

From panel one it can be seen that Study Area demand increases from about 1.3 million acre-feet (maf) in 2015 to between 1.5 and 1.8 maf in 2060. The Study Area demand growth across scenarios in 2060, however, is projected to be as low as 159 kaf or as high as 440 kaf. About half of the Study Area demand is expected to be met by other supplies.

TABLE C3-1
Summary Results of New Mexico Water Demand Scenario Quantification by 2060

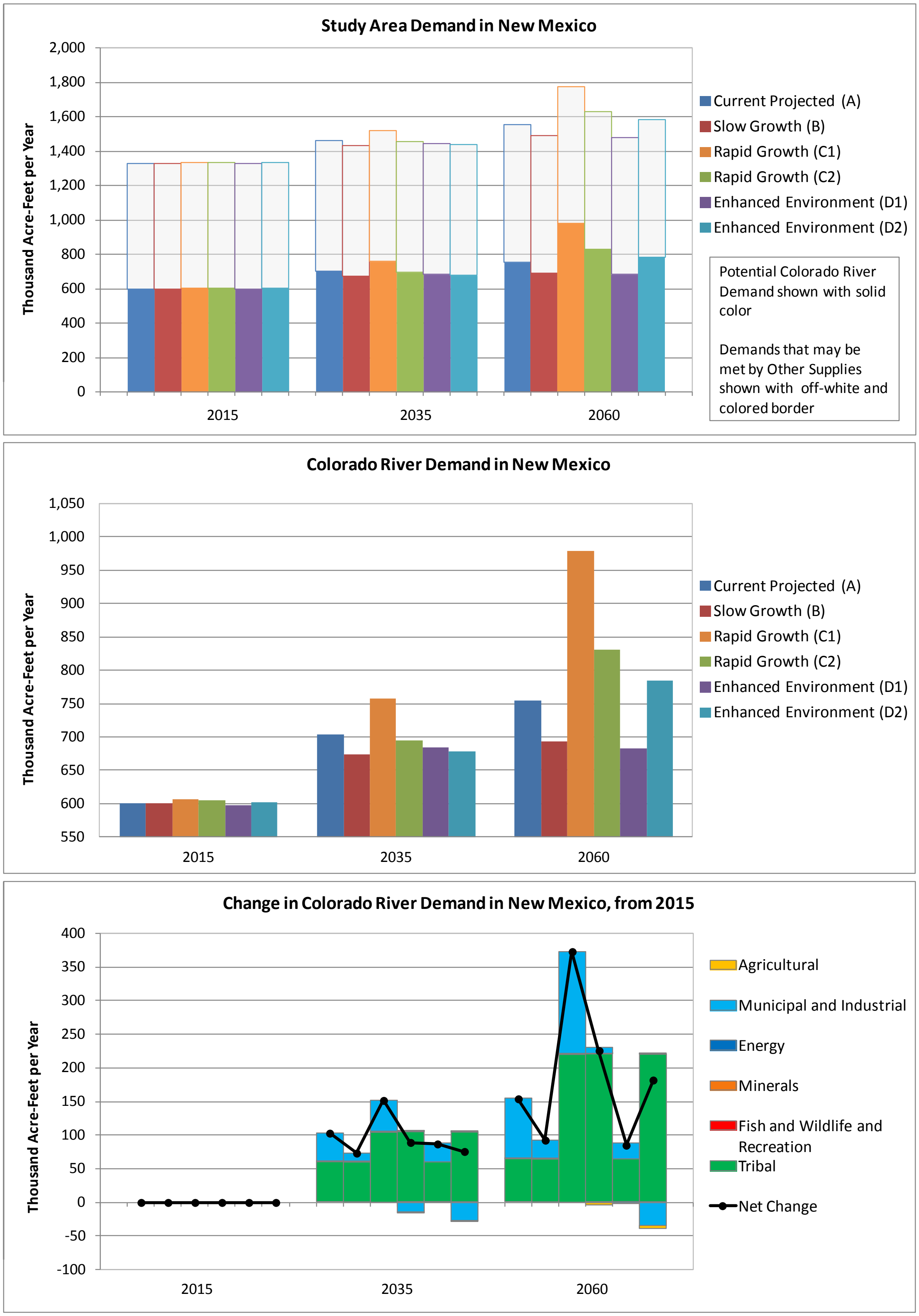
Key Study Area Demand Scenario Parameters							
	2015[1]	2060 Scenario Parameters					
		A	B	C1	C2	D1	D2
Population (millions)	1.5	2.6	2.0	3.0	3.0	2.6	3.0
Change in per capita water usage (%), from 2015	–	-11%	-11%	-11%	-15%	-24%	-22%
Irrigated acreage (millions of acres)	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Change in per acre water delivery (%), from 2015	–	+0%	+4%	+0%	-15%	+0%	-15%

Study Area Demand (thousand acre-feet [kaf])							
	2015[1]	2060 Scenario Demands					
		A	B	C1	C2	D1	D2
Ag demand	723	718	748	718	592	718	592
M&I demand	249–252	414	322	477	453	346	407
Energy demand	40.7	42.2	42.2	42.2	42.2	38.0	42.2
Minerals demand	6.2	6.2	6.2	6.2	6.2	6.2	6.2
FWR demand	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Tribal demand	303–309	367	367	529	529	367	529
Total Study Area Demand[2]	**1328–1337**	**1,551**	**1,490**	**1,777**	**1,627**	**1,480**	**1,581**

Colorado River Demand (kaf)							
	2015[1]	2060 Scenario Demands					
		A	B	C1	C2	D1	D2
Ag demand	111	111	111	111	106	111	106
M&I demand	138–141	230	169	293	149	163	102
Energy demand	40.0	41.5	41.5	41.5	41.5	37.4	41.5
Minerals demand	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FWR demand	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Tribal demand	303–309	367	367	529	529	367	529
Total Colorado River Demand[2]	**598–606**	**754**	**693**	**979**	**831**	**683**	**785**

[1] Range across scenarios.
[2] Excludes potential losses (reservoir evaporation, phreatophytes, and/or operational inefficiencies) that may be charged to state.

FIGURE C3-2
Study Area, Colorado River, and Change in Colorado River Demand

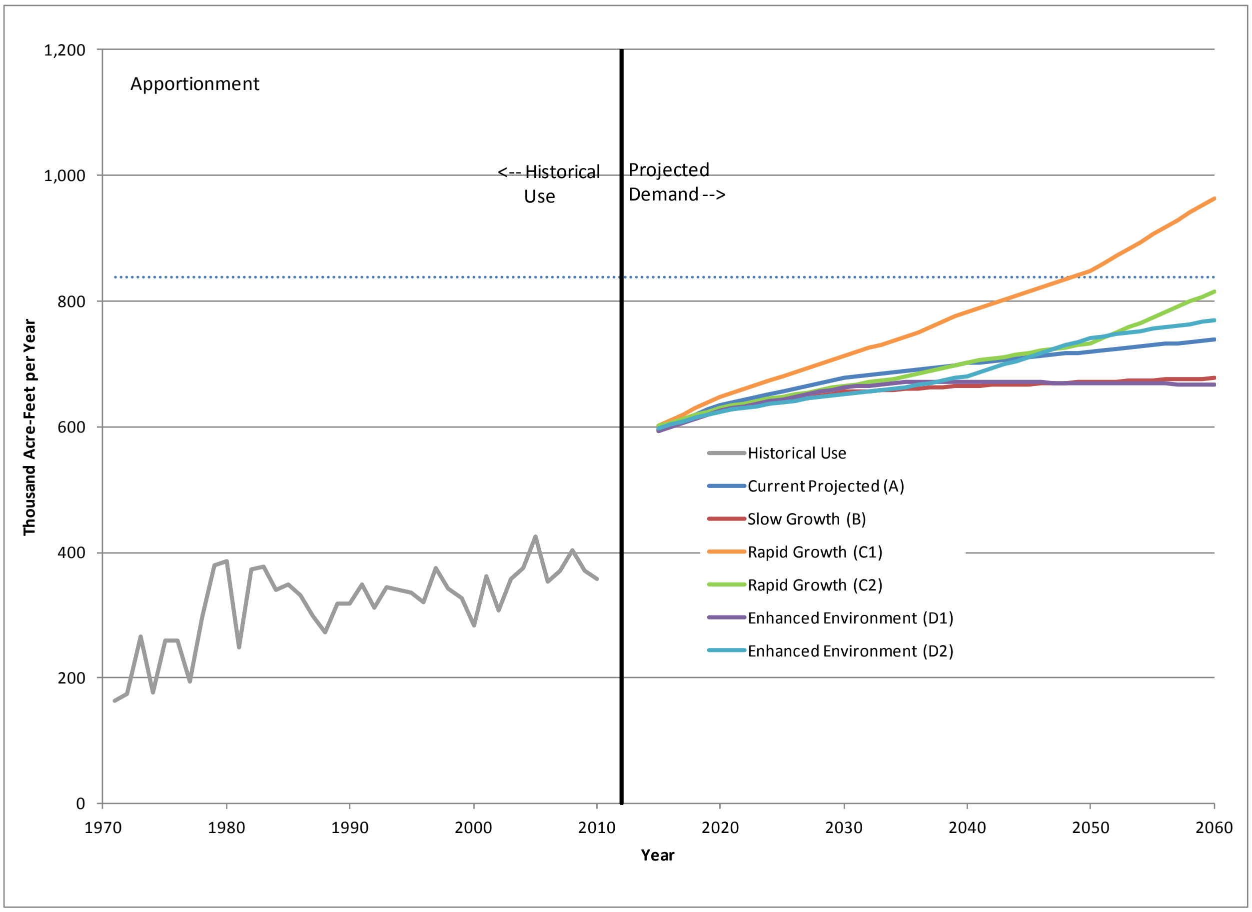


Panel two provides a view of the range across scenarios of Colorado River demand. This demand increases from about 600 kaf in 2015 to between 683 and 980 kaf in 2060 (or 14 to 62 percent), depending on the scenario. This difference results in a Colorado River demand range of 297 kaf across the scenarios in 2060, or about 40 percent.

Panel three shows how specific categories affect the projected change in Colorado River demand by scenario. Growth in tribal demand across all scenarios results in the greatest increase in demand (between 41 and 100 percent), followed closely by M&I demand (between 3 and 60 percent).

Figure C3-3 ties historical water use to the range of Colorado River demand in the quantified scenarios. The nearly 300 kaf range across scenarios in 2060 is easily discernible, with a relatively even spread over the range across the scenarios.

FIGURE C3-3
Historical Use and Future Projected Demand Excluding Reservoir Evaporation[1]



[1] Reservoir evaporation on the order of 70 kaf is not included in this plot.

3.2 Colorado River Water Demand by Geography

Colorado River water demand for areas served by the Colorado River is presented in figures C3-4 and C3-5. These figures show two geographic levels: Study Area in New Mexico, and individual planning areas. Demands at each geographic level are shown across the scenarios. The columns to the right show the Colorado River demand at a point in time (2015, 2035, or 2060) by relative contribution of the categories.

Colorado River demand[2] in New Mexico is primarily in the San Juan and Adjacent Areas planning areas. The San Juan planning area has the greatest magnitude of Colorado River demand, with tribal demands making up the majority of those demands, along with some energy and agricultural demands. The primary demand category in the Adjacent Areas planning is M&I, with a small amount of agricultural demand.

Figure C3-6 shows the change in Colorado River demand by category from 2015 across the scenarios. Change in Colorado River demand is roughly similar in magnitude on both the San Juan and Adjacent Areas planning areas, with tribal demand making up the vast majority of change in San Juan, and M&I making up all of the change in Adjacent Areas.

3.3 Colorado River Demand by Category

3.3.1 Agricultural

Agricultural water demand is driven by irrigated acreage and water delivery per acre. Water delivery per acre is the amount of water diverted per irrigated acre. Components of this use include transmission and delivery losses (surface evaporation, riparian demand, and seepage) and on-farm losses that are made up of evaporation, crop irrigation requirements, and tail water (return). Each of these factors will vary by location (precipitation, growing season, etc.), irrigation method, and crop type.

Figure C3-7 presents the following by scenario in 2015, 2035, and 2060:

- Change in agricultural demand for Colorado River water
- Change in agricultural demand for Colorado River water by planning area
- Agricultural demand as a portion of Colorado River water demand (right hand side of graph)

As can be seen from figure C3-7, agricultural water demand[3] makes up 19 percent of Colorado River demand in New Mexico in 2015, and drops to between 11 and 16 percent of demand in 2060. This drop results from both a decrease in agricultural water demand and an increase in other categories of demand. The majority of Colorado River demand for agriculture is located in the San Juan planning area.

[2] Potential Colorado River demand is based on changes in parameters such as population and for the purpose of the Study is not limited by apportionment.

[3] Tribal demand currently includes a significant quantity of agriculture demand that is included in the tribal category and not represented here. Agricultural use in the tribal category continues to grow as settlements are implemented.

FIGURE C3-4
Colorado River Demand in New Mexico

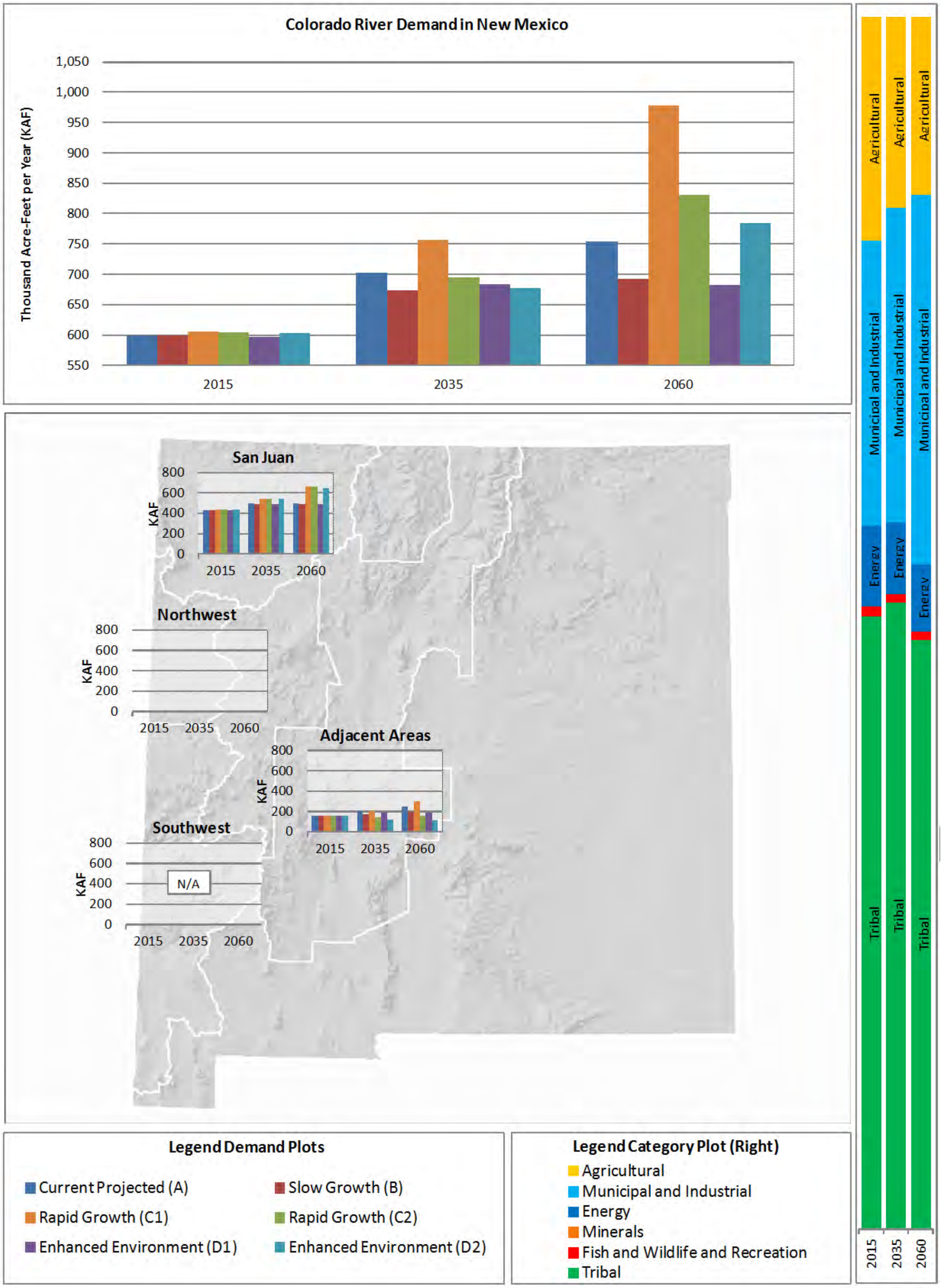


FIGURE C3-5
Colorado River Demand by Category

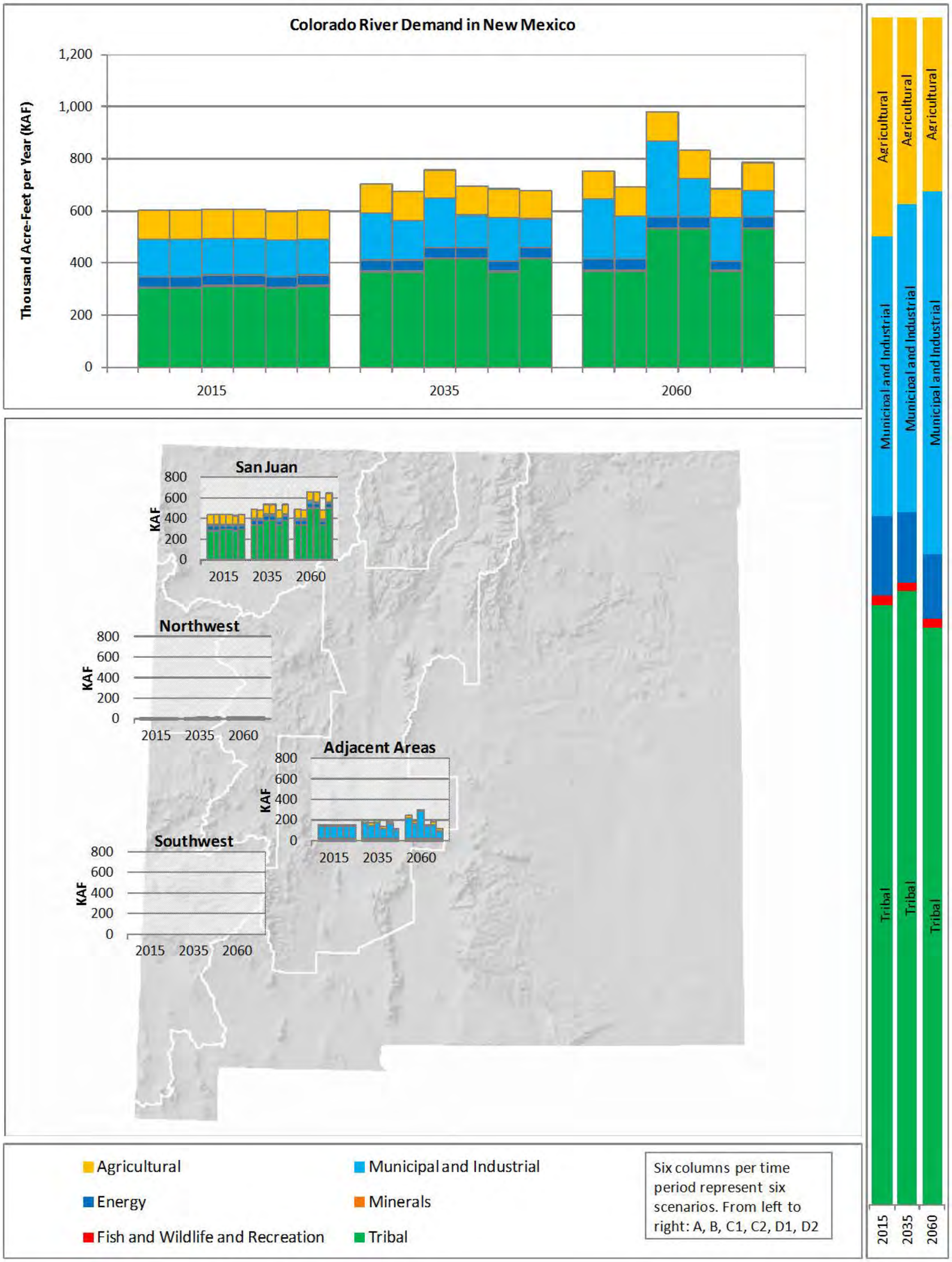


FIGURE C3-6
Change in Colorado River Demand in New Mexico from 2015 by Category

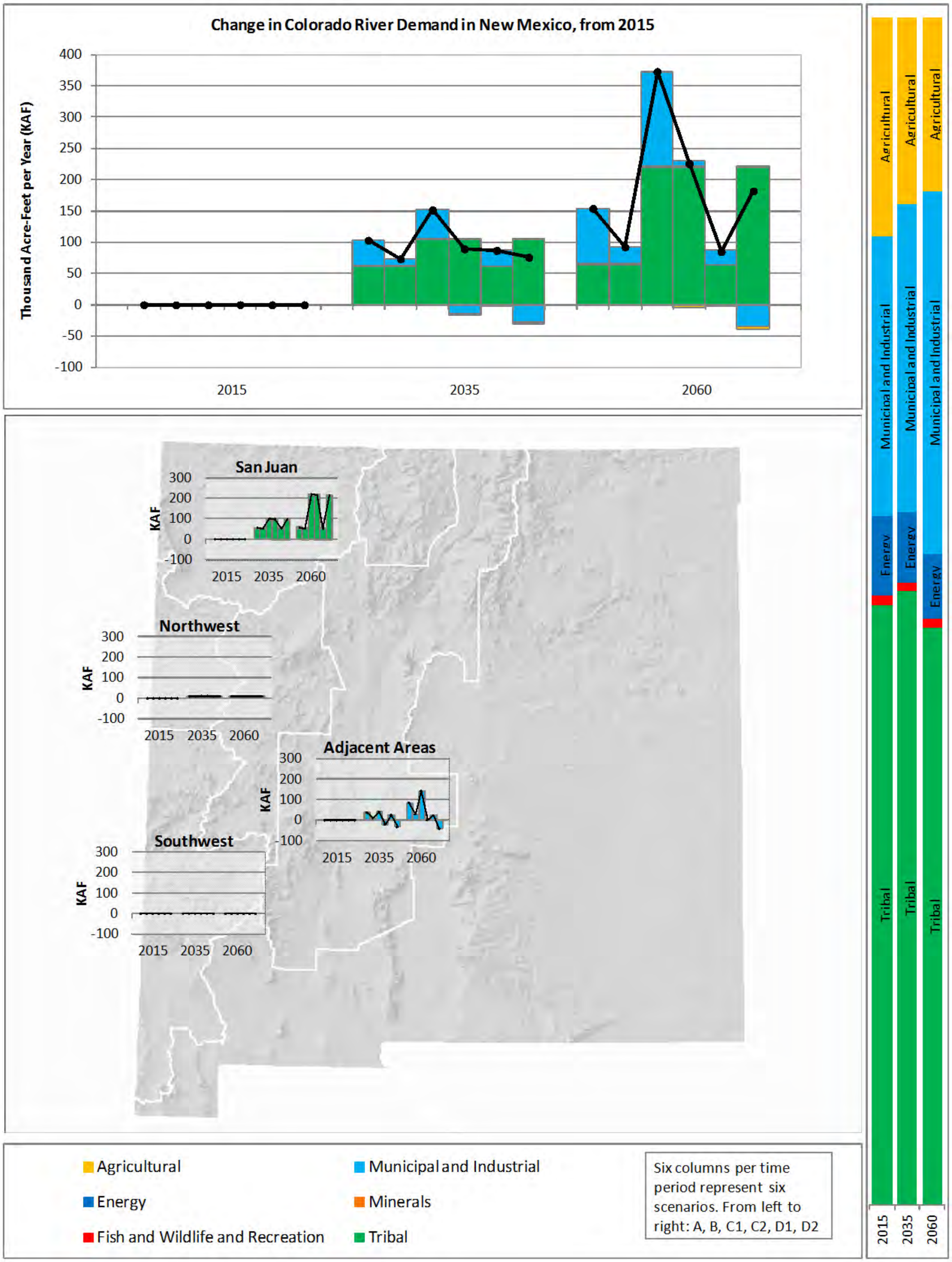
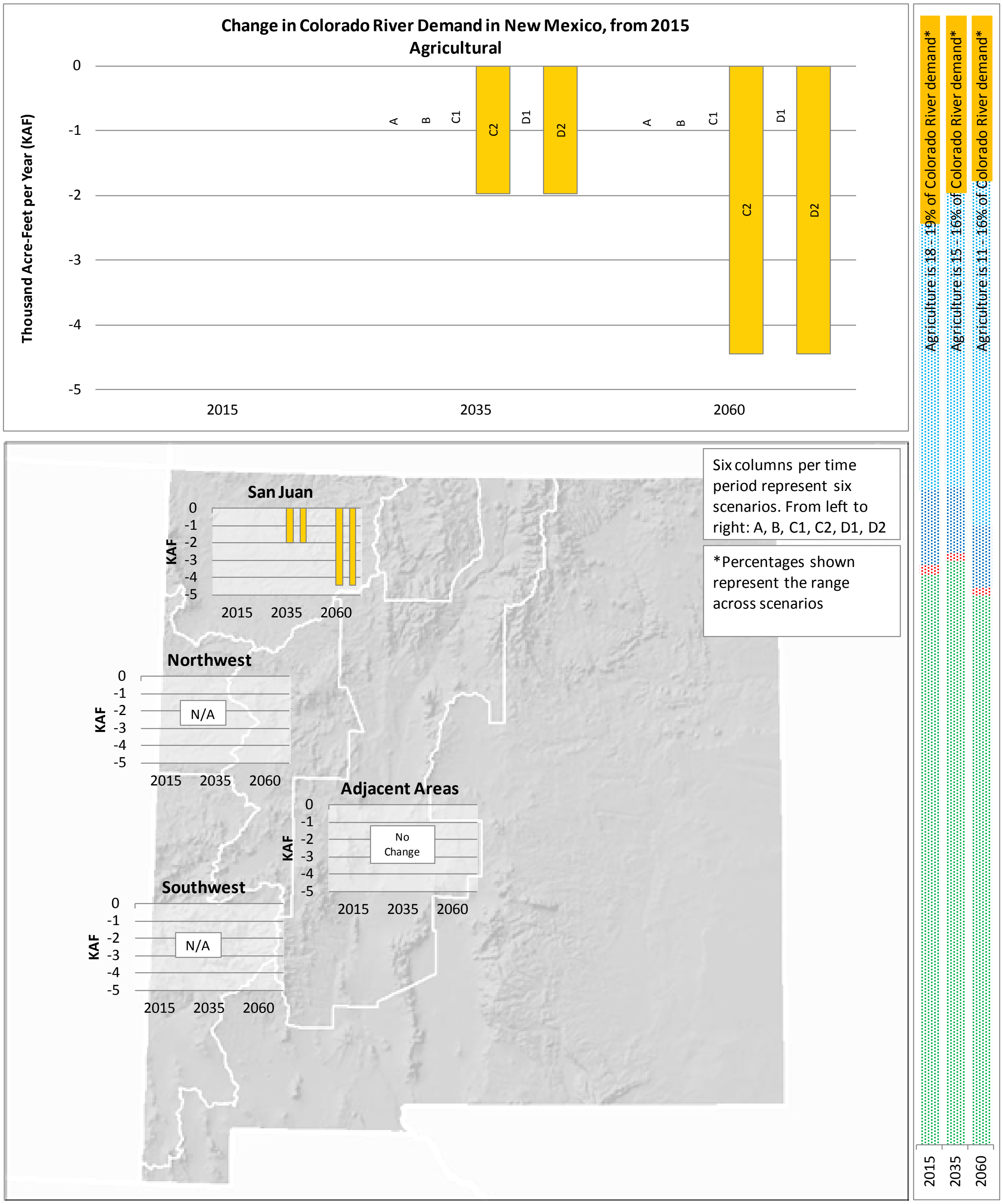


FIGURE C3-7
Change in Colorado River Demand in New Mexico from 2015 for Agriculture



In the San Juan planning area, Colorado River demand for agriculture decreases in the Rapid Growth (C2) and Enhanced Environment (D2) scenarios, by about 4.5 kaf (5 percent of Colorado River demand). The decrease is due entirely to reduced water delivery per acre; irrigated acreage is forecast to remain constant in the San Juan planning area across all scenarios. Colorado River demand for agriculture in all other planning areas is forecast to remain constant through time across all scenarios.

3.3.2 Municipal and Industrial

M&I water demand can be estimated from population and M&I per capita water use, with the addition of self-served industrial (SSI) demand. M&I per capita water use is a measure of the amount of water produced or diverted per person in a given municipality. Because this measure examines all water produced by a given municipality, it often includes industrial, commercial, and institutional demand as well as residential demand. A number of factors may influence the M&I per capita water use of a given community, including the amount of industrial demand, climate, number of institutional facilities, and number of visitors.

SSI are industries located in a given area that have their own water supply systems and are therefore not directly related to local measures of population and M&I per capita water use.

Figure C3-8 presents the following by scenario in 2015, 2035, and 2060:

- Change in M&I demand for Colorado River water in the Study Area
- Change in M&I demand for Colorado River water in individual planning areas
- M&I demand as a portion of Colorado River water demand (right hand side of graph)

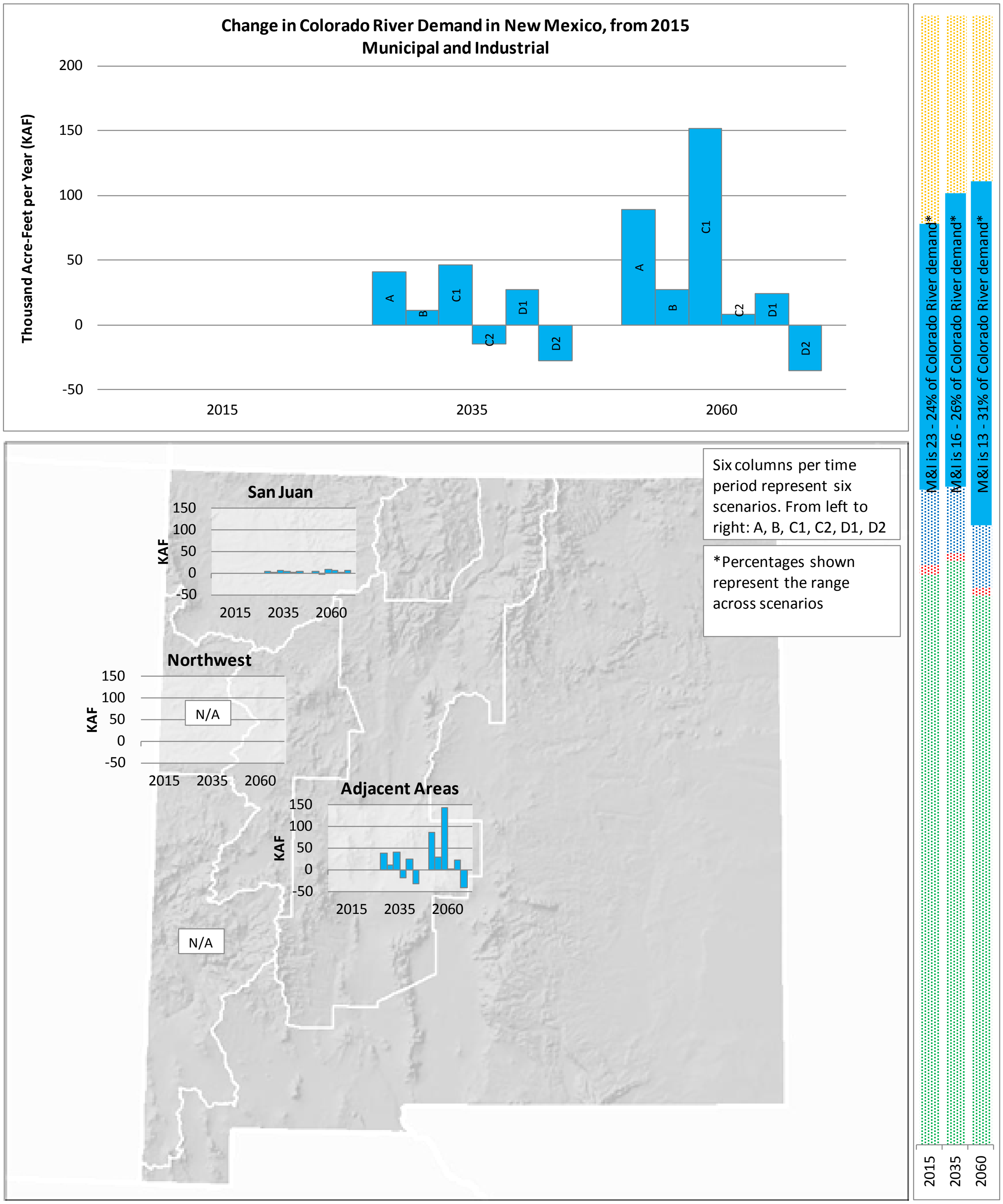
As can be seen from figure C3-8, M&I water demand is the second-largest component of Colorado River demand, changing from 24 percent in 2015 to between 13 and 31 percent of Colorado River demand in 2060, depending on which scenario is considered.

Colorado River demand for M&I use increases over time from 2015 to 2060 in the Current Projected (A), Slow Growth (B), Rapid Growth (C1), and Enhanced Environment (D1) scenarios. This increase is primarily due to population increase, as M&I per capita water use decreases over time across all scenarios and SSI demand nominally increases. Decrease in the M&I demand in the Rapid Growth (C2) and Enhanced Environment (D2) scenarios is due to decrease in per capita water use.

In examining the planning areas, nearly all of the increase in M&I demand for Colorado River water from 2015 to 2060 over time is due to population increase in the Adjacent Areas across all scenarios. The remaining increase in demand is primarily from M&I demand in the San Juan planning area.

Increases in population are somewhat tempered by decreases in M&I per capita water use. Per capita water use decreases in all scenarios with reductions ranging from 11 to 24 percent by 2060.

FIGURE C3-8
Change in Colorado River Demand in New Mexico from 2015 for M&I



3.3.3 Energy

Water demand for energy can be estimated through known plans for new power plants or through applying a per capita energy water use factor. Power facilities often serve areas remote from their locations and therefore potentially represent exports or imports of water from the Study Area to meet these distributed needs.

Figure C3-9 presents the following by scenario in 2015, 2035, and 2060:

- Change in energy demand for Colorado River water
- Change in energy demand for Colorado River water in individual planning areas
- Energy demand as a portion of Colorado River water demand (right hand side of graph)

As can be seen from figure C3-9, energy water demand is a relatively small fraction of Colorado River demand, decreasing from 7 percent of in 2015 to between 4 and 6 percent of demand in 2060, depending on which scenario is considered. The decreasing percentage is due to demands in other categories increasing at a faster rate than energy demands increase.

Energy demand for Colorado River water increases over time from 2015 to 2060 across all scenarios, with notable increases for the Current Projected (A) and Rapid Growth (C1) scenarios.

Energy demands are shown only in the San Juan planning areas. Consistent increases occur in the San Juan planning area across all scenarios, with an increase of 1.5 kaf to a total of 41.5 kaf.

3.3.4 Minerals Extraction

Although there is some demand for minerals in the Southwest (about 900 afy in Current Projected [A] scenario) and the Adjacent Areas (about 5,300 afy in Current Projected [A] scenario), these demands are met by other supplies. There is no reported Colorado River demand for minerals extraction under the scenarios analyzed for the Study.

3.3.5 Fish, Wildlife, and Recreation

There are no reported consumptive fish, wildlife, and recreation demands on Colorado River water in New Mexico.

3.3.6 Tribal

Tribal water demands were provided by the Jicarilla Apache Nation and the Navajo Nation in cooperation with the State of New Mexico. The projected Navajo Nation demands were provided by the Navajo Nation Department of Water Resources and modified to fit the storyline narratives regarding tribal use under each scenario.

Figure C3-10 presents the following by scenario in 2015, 2035, and 2060:

- Change in tribal demand for Colorado River water
- Change in tribal demand for Colorado River water in individual planning area
- Tribal demand as a portion of Colorado River demand (right hand side of graph)

FIGURE C3-9
Change in Colorado River Demand in New Mexico from 2015 for Energy

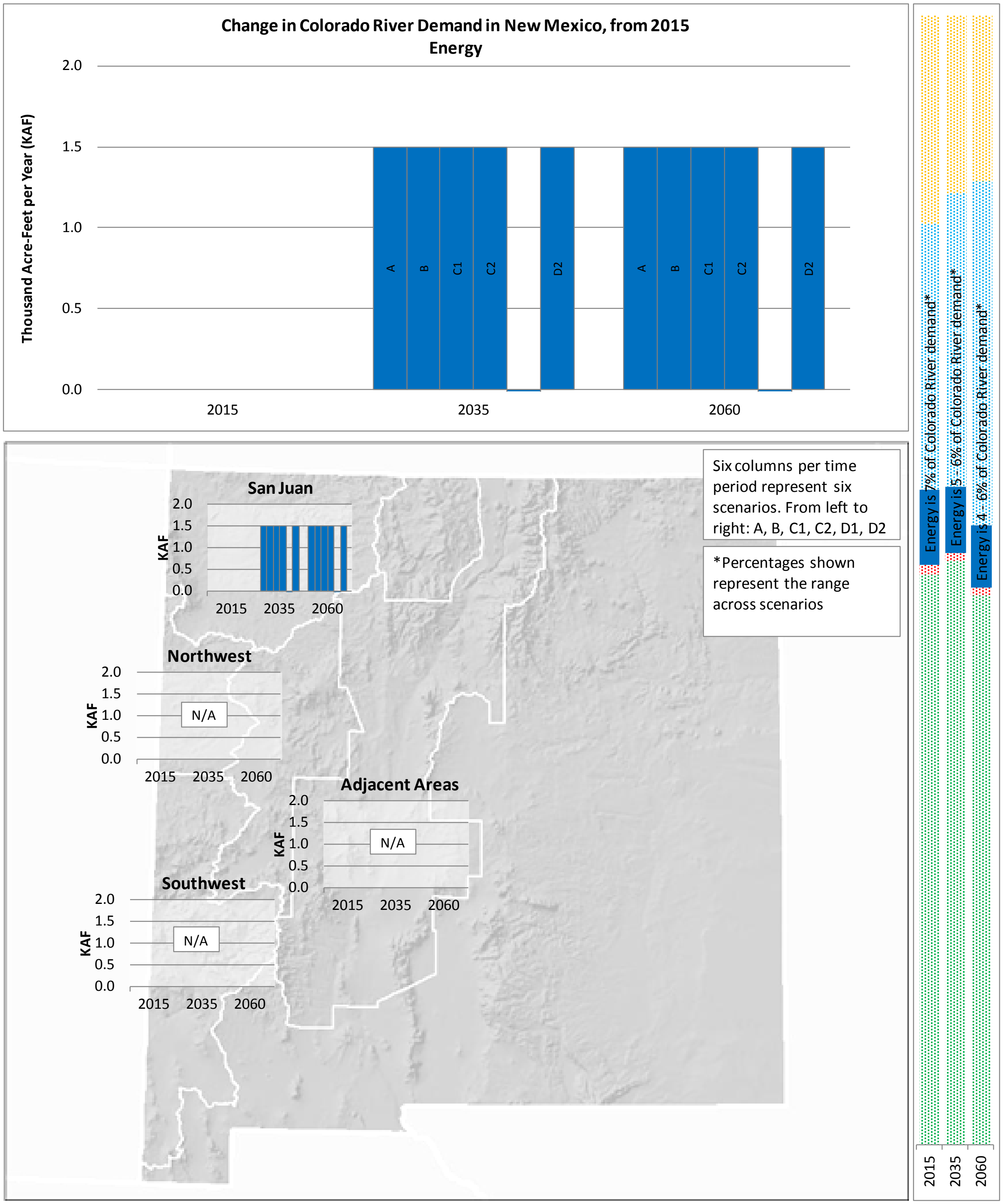
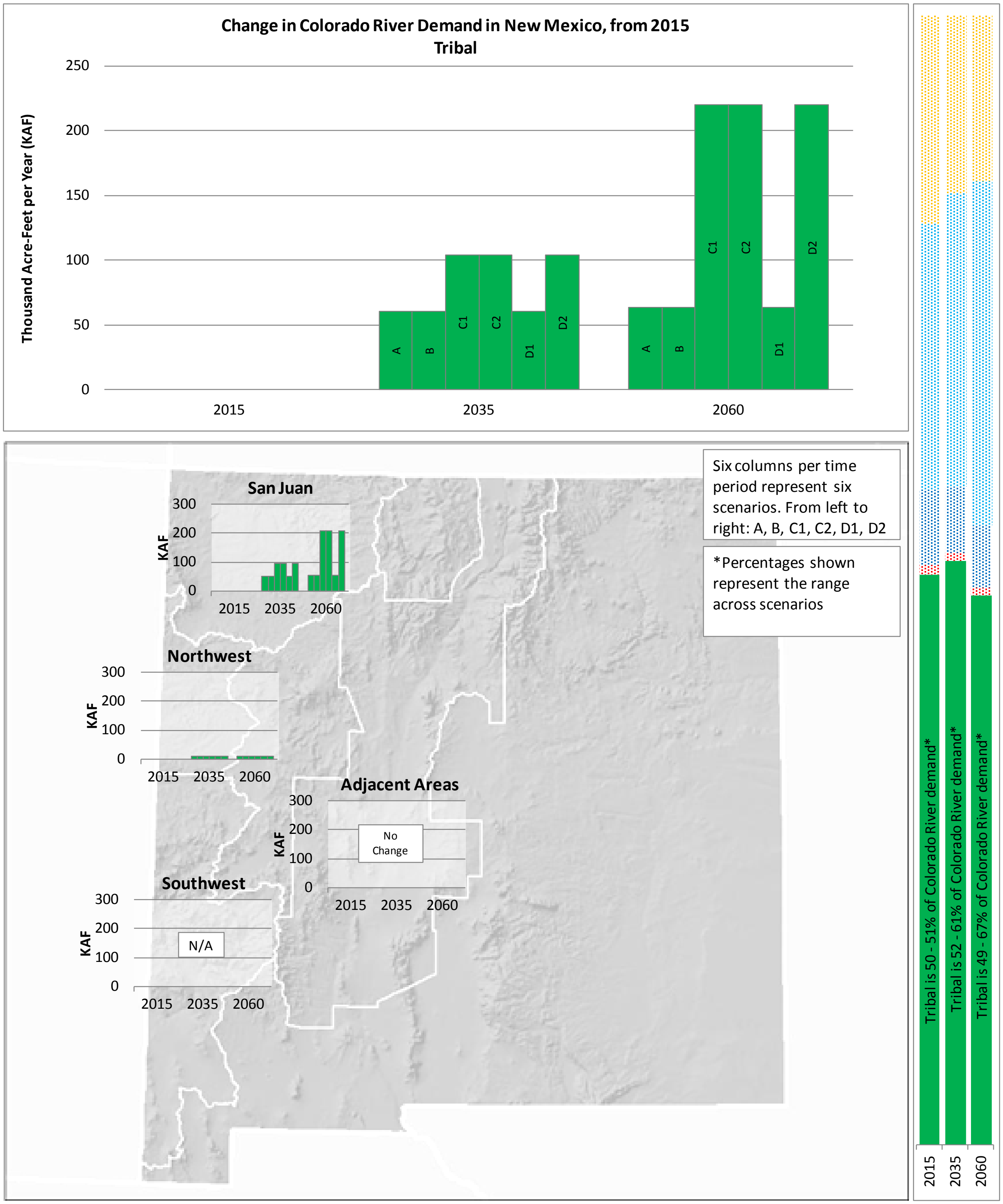


FIGURE C3-10
Change in Colorado River Demand in New Mexico from 2015 for Tribal



As can be seen from figure C3-10, tribal water demand is the largest component of Colorado River demand in New Mexico, decreasing from about 50 percent in 2015 to between 49 and 67 percent of Colorado River demand in 2060, depending on which scenario is considered. The decreasing percentage is due to demands in other categories increasing at a faster rate than tribal demands increase.

Colorado River tribal demand increases over time from 2015 to 2060 across all scenarios. These increases are primarily due to development of demands under water rights settlements. Increases occur mostly in the San Juan planning area, but there is also some increase in the Northwest planning area. The rate of increase is similar across all scenarios.

For additional information on tribal water demands, see appendix C9.

3.4 Summary Tables of Parameters and Demands by Category

Tables C3-2 to C3-7 present the specific parameter data collected by planning area. Each table is a complete set of data for a given scenario. These data were used to develop Study Area demands and subsequently Colorado River demands once other supplies were considered. These tables provide the specific information used in the creation of the summary and category plots previously discussed and provide reference information for the data provided.

4.0 References

Bureau of Business and Economic Research (BBER). 1993. *Population Growth Trends for the Upper Rio Grande and Albuquerque.*

Bureau of Business and Economic Research (BBER). 2008. *A Report on Historical and Future Population Dynamics in New Mexico Water Planning Regions.*

Daniel B. Stephens & Associates (DBSA). 2005. *Southwest New Mexico Regional Water Plan.* Prepared for Southwest New Mexico Regional Water Plan Steering Committee, City of Deming, New Mexico, Fiscal Agent. Accepted by New Mexico Interstate Stream Commission, 2005.

Daniel B. Stephens & Associates (DBSA). 2008. *Taos Regional Water Plan*. Prepared for Taos Regional Water Planning Steering Committee. Accepted by New Mexico Interstate Stream Commission, 2008.

New Mexico Interstate Stream Commission (NMISC). 2011. Personal communication with Reclamation.

San Juan Water Commission. 2003. *San Juan Regional Water Plan*.

S.S. Papadopoulos and Associates (SSPA). 2000. *Middle Rio Grande Water Supply Study*.