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Alternative Management Paradigms for the Future of the Colorado and Green Rivers

Kevin Wheeler, Eric Kuhn, Lindsey Bruckerhoff, Brad Udall, Jian Wang, Lael Gilbert, Sara Goeking, Alan Kasprak, Bryce Mihalevich, Bethany Neilson, Homa Salehabadi and John C. Schmidt

An exploration of wide-ranging alternatives for sustainably managing the future water supply, with consideration for their effects on ecosystems.

Alternative Management Paradigms for the Future of the Colorado and Green Rivers

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“The likelihood of conflict rises as the rate of change within the basin exceeds the institutional capacity to absorb that change.”

Wolf, A. T., S. B. Yoffe and M. Giordano (2003). "International waters: Identifying basins at risk." Water policy 5(1): 29-60.

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Part 1. The Past and Exploring the Possibilities

1. Introduction

The Colorado River is among the most extensively managed river systems in the world. The river's headwaters are within the Rocky Mountains in the United States. From there, it flows through the arid lands of the Colorado Plateau and the Basin-and-Range to its delta in northwestern Mexico. Here, the river is the only significant water supply in an otherwise starkly arid landscape and has long been called "America's Nile." It provides a critical water supply for nearly four million acres of irrigated land, municipal supplies for 30 million people located within and outside the basin, and more than 4,200 MW of hydropower generation capacity. The Colorado River and some of its tributaries also provide an existing or potential water supply for at least 15 Native American tribes. The river flows through seven National Wildlife Refuges, four National Recreation Areas, and five National Parks.

Today, the annual consumptive uses and losses of streamflow in the basin typically exceed the amount of water available, and the river rarely flows into the Gulf of California. The impacts of climate change are likely to decrease future runoff and intensify droughts, thereby threatening current and future uses in the basin. **Clearly, new ways of thinking about and managing the river need to be sought and implemented.**

The high degree of management on the river is facilitated by extensive infrastructure. The reservoir storage capacity of the basin is approximately four times the average annual flow of the river, allowing the watershed's runoff to be controlled by dozens of large dams and hundreds of smaller structures constructed since the early 1900s. Notable dams in the watershed include the iconic Hoover Dam completed in 1936 and Glen Canyon Dam completed in 1963, which form Lake Mead and Lake Powell, respectively.

The Colorado River also boasts one of the most institutionally and administratively complex landscapes of any major river in the world. Guided by the *Law of the River*—a multi-layered assortment of international agreements, interstate compacts, legal decrees, operational criteria, federal and state regulations, and local management plans—river managers attempt to meet water-related needs in seven states in the United States and two states in northwestern Mexico. The majority of consumptive water use is for irrigated agriculture, municipalities, and industry, and non-consumptive uses include hydropower, recreation, and river ecosystems. Furthermore, different parts of the river corridor are sacred to various Native American tribes, and the dramatic landscapes shaped by the river over geologic time hold an intrinsic value described through stories, lore, poetry, and history.

Society's sophisticated ability to regulate streamflow and distribute water to its many users has profoundly transformed riverine ecosystems. Historically, negotiations concerning key aspects of the *Law of the River* focused on water allocation and did not explicitly consider ecosystem outcomes. For example, interstate agreements that regulate the distribution of water storage between Lake Powell and Lake Mead have resulted in large 'equalization' releases from Lake

Powell, but the implications of those releases on ecosystems in the Grand Canyon were not substantially considered. However, forthcoming negotiations over water allocation and reservoir management allow for an opportunity to re-examine the distribution of water storage between Lake Powell and Lake Mead, and to reconsider the releases to meet both consumptive and non-consumptive needs.

Water management decisions have major implications for ecosystems due to the relationships between water storage, downstream hydrology, temperature, and sediment supply. Water storage can influence both the magnitude and timing of high and low flows that serve as cues for critical life stages of fish and other taxa (Lytle and Poff, 2004). Releases from full reservoirs are typically cooler than those from relatively empty reservoirs. Because river temperature is an important determinant of the characteristics and processes within aquatic ecosystems (Dibble et al., 2020), decisions about where and how much water to store and release from reservoirs profoundly affect those ecosystems. Sediment trapping also causes sediment deficit conditions downstream from these reservoirs that, in turn, leads to incision of the channel bed, disconnection of the floodplain ecosystem from the river's hydrology, and erosion of valued river resources. Releases with low turbidity cause altered heat absorption rates and increased threat to native fish from sight-feeding predators. The premise of our work is that the ecosystem conditions resulting from future water allocation agreements can be anticipated, ought to be explicitly considered throughout forthcoming negotiations, and should be part of the decision-making process.

The purpose of this white paper is to encourage broad thinking about how the Colorado River might be managed sustainably in the future, especially as water users confront declining watershed runoff resulting from climate change and persistent droughts. We view our role as to provide provocative suggestions that some might consider beyond the framework of present interpretations of the *Law of the River,* but might nevertheless meet society's water supply needs and yield more desirable ecosystem outcomes. Our effort to articulate these 'out-of-the-box' policy options is intended to encourage their consideration during the renegotiation of basin-wide Shortage Guidelines concluding in the mid-2020s. We understand that any policy we propose will be evaluated and refined by water managers and stakeholders; our effort here is to provide an initial framework for novel thinking.

We refer to the policies that we articulate and analyze as *alternative management paradigms (AMPs)*. These alternatives may initially seem radical to some, but we maintain that such policies may not be viewed as radical in an era of increasing climatic and societal uncertainty. In previous decades, water managers have adopted an incremental adaptation approach. However, a declining water supply, the increasing probability of prolonged droughts, urban growth, and a growing focus on the environmental implications of water management should encourage a more wide-ranging evaluation process. Through our analysis, we evaluate whether the future reliability of water supply using current management practices can be maintained or improved through different management approaches under increasing risks from climate changes and persistent droughts.

Our primary findings indicate the planning and management strategies implemented today will not be adequate to meet management objectives under likely future hydrologic conditions. This inadequacy will be apparent in the near future if the drought that has persisted since 2000 continues, and the inadequacy would be exacerbated if a drought similar to that estimated to have occurred in the 1500s returns. It is important to consider the possibility that the current drought may be a 'new normal' rather than a temporary condition that will pass. However, if projected climate change conditions were to occur, a 'new abnormal' condition might now exist, and we show that in this case, even current uses of the Colorado River are not sustainable. Additionally, we show that projected increases in depletions would worsen the imbalance between water supply and consumptive water use.

Our findings also indicate that reservoir operations of Lake Powell and Lake Mead can be modified, under currently expected as well as drought conditions, to yield substantially different ecosystem outcomes. However, we also find that significantly modified distribution of storage between the reservoirs will not significantly improve nor further jeopardize the sustainability of water supplies. In other words, we can improve ecosystem outcomes by operating the reservoirs in a different way, but we cannot operate our way out of a water scarcity crisis.

While some of the alternative management paradigms we consider are likely to require significant adaptations to the institutional arrangements that currently exist, our findings demonstrate that alternatives do indeed exist which can better sustain the future of the Colorado River under unprecedented changes.

2. Background

The river network can be delineated into four regions based on the degree to which flow is regulated and the channel physically manipulated: the Upper Basin, the Grand Canyon, the lower river between Lake Mead and Morelos Dam, and the Delta (Schmidt, Bruckerhoff et al., in prep) (Figure 2.1). Relatively large amounts of water still flow through most of the channels of the Upper Basin and enter Lake Powell with approximately natural seasonality, although somewhat modified by Upper Basin dams and diversions. Flows through the Grand Canyon, however, are greatly affected by the existence and the operating rules of Glen Canyon Dam (Wheeler et al., 2019) which alters the downstream timing of flows. The lower river downstream from Hoover Dam is progressively depleted by large diversions to meet California, Arizona, and Mexico's consumptive uses. Downstream from these diversions, the channel in the delta is dry except for minimal agricultural return flows and pilot restoration efforts (King et al., 2014; Pitt et al., 2017).

Between 1906 and 2018, the natural annual runoff in the Colorado River Basin has varied between 6.3 and 26.0 million acre-feet (maf), with an average of 16.0 maf (Salehabadi et al., 2020). The large storage capacity of the reservoirs provides water managers with significant tools to buffer the annual variability and strategically allocate water to its many uses. This spatial pattern of the upstream watershed with relatively natural flows, and the lower river and delta that are extensively regulated and depleted of flow, is the result of both infrastructure development and the current implementation of the *Law of the River*. Consequently, the integrity and attributes of riverine ecosystems differ greatly among these four regions.

The mainstem Colorado River and its large headwater tributaries (hereafter, the Colorado River network) are strongly affected by the fragmentation caused by numerous large dams and by the amount and quality of water released from them. The physical conditions downstream from the Colorado River's large reservoirs have changed significantly since the major dams were constructed. The flow regime of these rivers—i.e. the annual, monthly, and daily patterns of reservoir releases—are substantially different from the natural pre-dam conditions in the Grand Canyon, lower river, and delta. The large reservoirs are thermally stratified, and releases from these reservoirs are typically cooler than natural summer conditions. The large dams also completely trap the downstream sediment supply and organic debris flux, and affect other aspects of water quality.

Figure 2.1. Map showing the Colorado River Basin and surrounding areas that use Colorado River Water. Four regions are delineated, based on the degree to which flow is regulated and the channel physically manipulated: 1) the Upper Basin, 2) the Grand Canyon, 3) the lower river between Lake Mead and Morelos Dam, and 4) the Delta. The base map was adapted from Reclamation's 2012 Basin Study (USBR, 2012) *to include the entire Colorado River delta and Salton Trough within the United States and Mexico. This map also shows the areas in Mexico outside the watershed that are served by Colorado River water.*

The aquatic ecosystems of the Colorado River network are impacted by these physical conditions. These ecosystems include native and endemic species, some of which are federally listed as endangered or threatened, and non-native species, some of which are valued for recreational fishing. Other river resources, such as riparian ecosystems, recreational boating, camping, and cultural/archaeological sites are also strongly affected by the existence and operations of reservoirs and by streamflow diversions. We define river resources to include riparian and aquatic ecosystem attributes, landscape attributes of river corridors explicitly managed by the National Park Service, recreational attributes of rivers, and the cultural heritage that the river provides to Native Americans and to those who value the history of river exploration. The goals of river resource management differ among segments of the Colorado River and are guided by requirements of the Endangered Species Act, the mandates of the National Park Service, the goals of different adaptive management programs, and the economic value of recreational fishing and boating. Additionally, there are well-established economic benefits that river resources provide. No less important is the social, cultural, and economic value of reservoir recreation. In 2018, annual visitation at Lake Mead National Recreation Area (NRA) and Glen Canyon NRA was 7.5 and 4.2 million people, respectively.

To date, negotiations over water management have been primarily driven by concerns about water-supply reliability and security to support ~40 million people who use the Colorado River, and to a much lesser degree, by concerns about the broader river resources. River managers focusing on water supply have an unparalleled ability to intentionally, or unintentionally, alter flow and thermal regimes in the river segments of the Colorado River network. In this sense, the ecosystem impacts of climate change and declining watershed runoff might be exacerbated or ameliorated by societal and political agreements about water supply management (Dibble et al., 2020).

Substantial new management decisions on the Colorado River are likely in the future because three elements of the *Law of the River* will expire in 2026: the 2007 *Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead* (hereafter, Interim Guidelines; USDOI, 2007), the 2019 *Drought Contingency Plan* (DCP, 2019) agreement among the seven Basin States in the United States, and *Minute 323* of the 1944 Bi-National Water Treaty between the United States and Mexico. All three elements sought to manage the Colorado River in response to conditions of increasing drought and shortages. Renegotiation of these agreements will begin in 2021, and we seek to provide a scientific foundation whereby the impacts to river resources might be explicitly considered as part of the water-supply deliberations.

2.1. The *Law of the River*

The term *Law of the River* refers to the “ever-evolving compendium of documents relating to the management of the Colorado River” (Verburg, 2010). The Colorado River Compact (1922 Compact) is the foundation of the *Law of the River.* The Compact was signed on November 24, 1922, but was not formally ratified until February 1944, when Arizona unconditionally agreed to the terms of this agreement. Most aspects of the Compact became effective in June 1929 through an alternative strategy that involved passage of the Boulder Canyon Project Act (BCP, 1929).

The Compact divided the Colorado River watershed into two parts: the Upper Basin and the Lower Basin. The dividing point is at Lee Ferry, “a point in the main stream of the Colorado River one mile below the mouth of the Paria River.” The names Lee Ferry and Lees Ferry are often used interchangeably, but they are different places. While Lee Ferry is the specific geographic point delineated under the Compact, Lees Ferry is the site of the historic ferry crossing originally established by J. D.Lee in the late 1800s (Reilly, 1999) and is the location of a gaging station established on the Colorado River in 1921 just upstream from the confluence with the Paria River (Topping et al., 2003). Flow at Lees Ferry has been measured continuously since January 19, 1923. A gaging station was also established on the Paria River by October 1, 1923, and the flow of the Colorado River at Lee Ferry is calculated as the sum of the measured flow at both gages.

The 1922 Compact makes a distinction between the geographic definitions of each basin and the definitions of ‘the States of the Lower Division’—Arizona, California, and Nevada and ‘the States of the Upper Division’—Colorado, New Mexico, Utah, and Wyoming. Consumptive water use is allowed within any part of the States of the Upper and of the Lower Basin, regardless of whether or not that use occurs in the geographic boundary of the watershed.

Important provisions of the 1922 Compact include the term ’Colorado River System’ which means “that portion of the Colorado River and its tributaries within the United States of America,” and the five subparagraphs of Article III that concern water use.

- Under Article III(a), each basin is apportioned for beneficial consumptive use 7.5 million acre-feet per year (maf/year).
- Article III(b) allows the Lower Basin to increase its consumptive use by an additional one maf/year.
- Article III(c) anticipated a future international treaty with Mexico and provided that water for Mexico shall first come from any unallocated surplus of Colorado River streamflow. Surplus was defined as water in excess of the “aggregate of the quantities specified in paragraphs (a) and (b),” which is 16 maf. If the surplus is not sufficient to meet commitments to Mexico, then the deficiency is “equally borne between the Upper and Lower Basins.” When the Compact was negotiated, the commissioners believed that the total water available in the entire Colorado River System was more than 20 maf/year. Thus, the surplus was believed to be more than 4 maf/year (Kuhn and Fleck, 2019).
- Article III(d) requires that “the States of the Upper Division will not cause the flow of the river at Lee Ferry to be depleted to be less than an aggregate of 75 maf for any period of 10 consecutive years…” It is significant that this is a non-depletion requirement rather than a delivery obligation, and that this volume is a decadal, and not an annual, aggregation. Although the commissioners debated the matter, the Compact requires no annual flow at Lee Ferry.

- Article III(e) precludes the States of the Upper Division from withholding water and the States of the Lower Division from requiring the delivery of water that can not reasonably be applied to domestic and agricultural uses.

In addition to the 1922 Compact, three other substantial elements of the *Law of the River* specify allocations of water for consumptive use including: the 1944 Bi-National Water Treaty (Treaty, 1944), the 1948 Upper Colorado River Basin Compact (Compact, 1948), and the 1964 Supreme Court decree in Arizona v. California (Decree, 1964). The binational treaty, signed in 1944 and ratified by the U.S. Senate in 1945, assures a delivery to Mexico of 1.5 maf/year in years of normal flow. The treaty also includes shortage and surplus provisions. The treaty is interpreted and implemented through Minutes approved by the International Boundary and Water Commission (IBWC).

The Upper Colorado River Basin Compact (1948 Compact) divides the water available to the Upper Basin among the five states with lands in the Upper Basin, including Arizona and the four states of the Upper Division. Under the 1948 Compact, Arizona received a fixed apportionment of 50,000 acre-feet per year. The apportionments for the four Upper Division states are by percentages of the water available for use. Importantly, the provisions for a curtailment of Upper Basin uses to meet the requirements of the 1922 Compact, sometimes referred to as a ‘compact call,’ are included in the 1948 Compact, not the 1922 Compact.

There is no equivalent Lower Colorado River Basin compact. Historically, the allocation of Colorado River water among the three Lower Division states has been a very contentious issue. After the 1922 Compact was signed, Arizona refused to ratify the agreement, forcing the other six states to implement the alternative ratification strategy that is included in the Boulder Canyon Project (BCP) Act. Frustrated by California’s opposition to the authorization of its Central Arizona Project, Arizona filed suit in the United States Supreme Court in 1952. After a lengthy legal battle, the court issued a ruling in 1963. The decision, implemented through the decree issued in 1964, set the apportionments of mainstem water in and downstream from Lake Mead for Arizona, California, and Nevada as 2.8 maf, 4.4 maf, and 0.3 maf respectively. The decision avoided any interpretation of the Compact itself. Instead, the Supreme Court decision interpreted the intent of Congress when the BCP Act was passed. The decision also confirmed and strengthened the role of the Secretary of the Interior as the ‘water master' for Lower Basin water uses in and downstream from Lake Mead (Kuhn and Fleck, 2019).

The construction and operation of most of the federally built projects on the river were authorized pursuant to three major development acts; the 1928 BCP Act, the 1956 Colorado River Storage Project Act (CRSP Act, 1956), and the 1968 Colorado River Basin Project Act (CRBP Act, 1968). The BCP Act authorized the Boulder Canyon Project, now Hoover Dam, that created Lake Mead, and the All-American Canal. Additionally, the BCP Act provided Congressional approval of the 1922 Compact and allowed the Compact to become effective with only the approval of six states. The CRSP Act authorized the construction of Glen Canyon Dam, Flaming Gorge Dam, three dams on the Gunnison River now called the Aspinall Unit, and Navajo Dam. The CRSP Act also authorized a host of what are referred to as 'participating' projects that primarily provide agricultural water for use in the Upper Basin. The CRBP Act authorized the Central Arizona Project and several smaller projects in both basins. The CRBP Act also directed the Secretary of the Interior to prepare long-range operating criteria for the major storage reservoirs and to prepare a basin-wide consumptive uses and losses report every five years.

In addition to the compacts, international treaty, Supreme Court decree, and federal development acts, the *Law of the River* is further clarified by other state and federal laws, court decisions, contracts, and secretarial decisions. In some cases, there are different interpretations and conflicting documents that affect water-supply and river management. Thus, unresolved issues related to the *Law of the River* remain and fuel continued debate and discussion.

2.2. Operation of the Mainstem Reservoirs under the *Law of the River*

The operation of Hoover Dam and of the CRSP dams that include Glen Canyon Dam are governed by Section 6 of the CRBP Act which provides:

> In order to comply with and carry out the provisions of the Colorado River Compact, the Upper Colorado River Basin Compact, and the Mexican Water Treaty, the Secretary shall propose criteria for the coordinated long-range operation of the reservoirs constructed and operated under the authority of the Colorado River Storage Project Act, the Boulder Canyon Project Act, and the Boulder Canyon Project Adjustment Act.

The first coordinated Long-Range Operating Criteria (commonly referred to as the 'LROC') was adopted on June 4, 1970 (LROC, 1970). The LROC may be modified as needed and is formally reviewed every five years. The CRBP Act requires the Secretary to submit the LROC to the Governors of the seven Colorado River Basin States, and such other parties and agencies as the Secretary deems appropriate, for review and comment. The Grand Canyon Protection Act, passed in 1992, expanded the organizations and agencies with whom the Secretary must consult and expanded the purposes of operations of Glen Canyon Dam to include consideration of the resources of Grand Canyon National Park and Glen Canyon National Recreation Area.

Under the CRBP Act and the LROC, the priorities for releases from Glen Canyon Dam are:

- To satisfy the Upper Basin's obligation to Mexico under the 1944 Treaty, if any. However, neither the States of the Upper Division nor the States of the Lower Division have ever formally agreed on a quantification of the Upper Basin's obligation to Mexico.

- To satisfy the obligation of the States of the Upper Division under Article III(d) of the Colorado River Compact to not deplete the 10-year flow of the Colorado River at Lee Ferry to less than 75 maf.

To satisfy these two priorities, the 1970 LROC set an annual 'minimum objective release' of 8.23 maf/year from Glen Canyon Dam. The 8.23 maf/year is based on 7.5 maf/year, the annual average for delivery of water from the Upper Basin to the Lower Basin, plus 750,000 acre-feet/year, which is 50% of the 1.5 maf/year delivery to Mexico less 20,000 acre-feet/year which is the assumed average flow of the Paria River. To address concerns of the States of the Upper Division, the Secretary emphasized that the 8.23 maf/year release was an objective but not a requirement.

The LROC specifies that the annual release from Glen Canyon Dam can exceed 8.23 maf to equalize active storage contents of Lake Mead and Lake Powell if the Secretary determines there is sufficient storage in the Upper Basin to protect consumptive uses in the Upper Basin. These releases are commonly referred to as 'equalization' releases. Additional releases can be made to avoid spills or for dam safety purposes.

Hoover Dam is operated pursuant to the LROC and the 1964 Supreme Court decree in Arizona v. California. Water to be used for consumptive purposes can be pumped directly from Lake Mead or released from the Hoover Dam for the following specific purposes according to Article III of the LROC: Mexican treaty obligations, reasonable consumptive use requirements of mainstream users in the Lower Basin, net river losses, net reservoir losses and regulatory wastes.

The 1964 Supreme Court decree directs the Secretary to determine when surplus, normal, and shortage conditions exist. Under normal conditions, 7.5 maf/year is available for the Lower Basin consumptive uses. A surplus condition exists when the Secretary determines that more than 7.5 maf/year of water is available for Lower Basin annual uses from Lake Mead. A shortage condition exists when there is less than 7.5 maf/year available. Subject to specific provisions of the CRBP Act and Supreme Court decree, the Secretary has considerable discretion to implement the shortage and surplus provisions.

These conditions remained imprecisely defined for several decades. Meanwhile, California had begun diverting the unused apportionment of Arizona’s allocation. It eventually became clear that Arizona was capable of depleting their remaining allocation through the Central Arizona Project. The declaration of surplus conditions became a perceived administrative need, but not necessarily a hydrologic reality. Clearly, there was a growing need to codify both surplus and shortage conditions.

By 1999, the Secretary of the Interior had directed the Bureau of Reclamation to work with the Basin States to prepare and issue detailed and objective guidelines to assist in the determination of excess water availability, which would eventually be formalized in the Interim Surplus Guidelines (USBR, 2000), and subsequent Record of Decision. In 2005 in response to the first years of what is now referred to as the Millennium Drought (Salehabadi et al., 2020), the Secretary directed Reclamation to prepare Interim Shortage Guidelines and tools to meet the challenges of drought in the basin. In 2007, the Secretary approved the *Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead*, commonly referred to as the 2007 Interim Guidelines. The development of both guidelines relied heavily on the use of Reclamation’s primary planning tool, the Colorado River

Simulation System (CRSS), to develop and assess the important management options that were considered (Wheeler et al., 2019).

The 2007 Interim Guidelines formalized and quantified new shortage criteria for Lower Basin users and annual reservoir release amounts from Lake Powell and incorporated and replaced criteria defined in the 2001 Surplus Guidelines. Shortages to water users in the Lower Basin would be imposed if the Lake Mead pool elevation fell below 1075 ft msl (above mean sea level), and the volume of imposed shortages in the United States would reach up to 500,000 af/year if the pool elevation fell below 1025 ft msl. At Lake Powell, the 2007 Interim Guidelines defined a set of conditions in which annual releases would vary between 7 and 9.5 maf/year, depending on pool elevations in Lake Mead and Lake Powell. The criteria for defining when equalization releases were to occur was based on predicted end-of-water-year storage in Lake Powell. In the Record of Decision, the Secretary determined the 2007 Interim Guidelines are consistent with, and are to be used each year to implement, the LROC.

In 2019, in response to the prolonged nature of the Millennium Drought, the Secretary approved, and Congress passed legislation implementing supplemental drought contingency plans (DCPs) for each basin. Under the Lower Basin DCP, the three Lower Division States and the Bureau of Reclamation agreed to take additional actions to reduce annual deliveries from Lake Mead beyond the shortage amounts specified in the 2007 Interim Guidelines. The implications of the Upper Basin DCP were less specific, but included provisions to protect Lake Powell from falling below a ‘target elevation' of 3525 ft msl by invoking ‘drought operations’ of the upstream Flaming Gorge, Blue Mesa (the largest reservoir in the Aspinall Unit), and Navajo reservoirs. Furthermore, the DCP granted the ability of the Upper Basin States to ‘bank’ water in these federal reservoirs if the states eventually agree to an Upper Basin Demand Management program.

In 2018 and in anticipation of the adoption of the DCP, the IBWC adopted Minute 323 to the 1944 Binational Water Treaty. Minute 323 succeeded Minute 319 which was adopted in 2012, under which Mexico agreed to share shortages with other Lake Mead users. Under Minute 323, Mexico agreed to further reduce its uses of Colorado River water if drought persisted, and approximately in proportion to the shortages to which the Lower Basin States had committed. Table 2.1 shows the combined shortages from the 2007 Interim Guidelines, the DCP, Minute 319, and Minute 323. The amounts of additional conservation measures made pursuant to the Lower Basin DCP and Minute 323 were based on storage levels in Lake Mead. Mexico’s share ranged from 13 to 20% of the total contributions to reduce usage.

The 2007 Interim Guidelines, Upper Basin and Lower Basin DCPs, and Minute 323 will control reservoir operations and river management through the end of Water Year (WY) 2026. Basin-wide negotiations to develop guidelines to manage the river after 2026 are expected to begin in 2021.

Projected January 1 Lake Mead Elevation (feet msl)	2007 Interim Guidelines Shortages		2019 DCP Contributions			Combined Volumes			Lower Division States Total	Mexico			Total Lower Basin + Mexico	Contribution	
	AZ	NV	AZ	NV	CA	AZ	NV	CA		Minute 319	Minute 323	Mexico Total		USA	Mexico
At or below 1,090 and above 1,075	0	0	192	8	0	192	8	0	200	0	41	41	241	83.0%	17.0%
At or below 1,075 and at or above 1,050	320	13	192	8	0	512	21	0	533	50	30	80	613	86.9%	13.1%
Below 1,050 and above 1,045	400	17	192	8	0	592	25	0	617	70	34	104	721	85.6%	14.4%
At or below 1,045 and above 1,040	400	17	240	10	200	640	27	200	867	70	76	146	1013	85.6%	14.4%
At or below 1,040 and above 1,035	400	17	240	10	250	640	27	250	917	70	84	154	1071	85.6%	14.4%
At or below 1,035 and above 1,030	400	17	240	10	300	640	27	300	967	70	92	162	1129	85.7%	14.3%
At or below 1,030 and at or above 1,025	400	17	240	10	350	640	27	350	1017	70	101	171	1188	85.6%	14.4%
Below 1,025	480	20	240	10	350	720	30	350	1100	125	150	275	1375	80.0%	20.0%

Table 2.1. Shortages in thousands of acre-feet to Lower Basin States and Mexico under the 2007 Interim Guidelines, DCP, Minute 319 and Minute 323. *Note: This table does not include 100,000 acre-feet of conservation by the Secretary under Article III. b. of the LB DCP.*

2.3. Upper Basin Demands on the Colorado River

Development of the Upper Colorado River Basin began in the late 1800s with the construction of small and mid-sized diversions that developed the lands which could easily be reached by gravity diversions (Sibley, 2012). These lands were primarily in or near the existing flood plains. The small-scale diversions were supplemented by the construction of a few larger and more complex irrigation projects built by the U.S. Reclamation Service, which was the precursor to today’s Bureau of Reclamation. Examples of these Reclamation projects are the Uncompahgre Project in Colorado and the Strawberry Project in Utah. By 1922, when the Compact was negotiated, the estimated consumptive use in the Upper Basin was about 2.3 maf/year. After these easy-to-reach lands had been irrigated and first-generation Reclamation projects had been completed, the rate of increase in consumptive use of water in the Upper Basin slowed. By 1946 when the states with Upper Basin interests first met to negotiate the Upper Colorado River Basin Compact, the total annual consumptive use was still only about 2.5 maf/year (HD 419, 1947; Kuhn and Fleck, 2019).

What the 1948 Compact negotiators understood was that, except for a small number of projects built by the basin’s larger municipal water providers, future water development projects in the Upper Basin would have to be funded and subsidized by the federal government through Congressional appropriations and the construction of 'cash register' dams, like Glen Canyon. The Upper Basin development approach was implemented through the signing of the CRSP Act in 1956. This act authorized the construction of the initial storage units, Lake Powell, Flaming Gorge, Aspinall, and Navajo and the participating projects. The storage units provide water for uses within the Upper Basin, store additional water necessary for the States of the Upper Division to meet their 1922 Compact obligations during drought periods, and produce hydroelectric power. The participating projects included both local in-basin agriculture, municipal projects, and export projects that moved water out of the basin, such as the Central Utah Project and the San Juan-Chama Project. A portion of the revenues from the sale of hydroelectric power continues to be used to subsidize the irrigation components of participating projects.

The passage of the CRSP Act and the construction of several non-federal export projects by Colorado Front Range cities fueled an increase in Upper Basin consumptive uses from the late 1950s through the late 1980s. Since 1971, the Bureau of Reclamation, in consultation with the states, estimates and publishes detailed basin-wide consumptive uses and losses. The Consumptive Uses and Losses Reports are available online at https://www.usbr.gov/uc/envdocs/plans.html. The consumptive use data are continually upgraded and revised as better information becomes available. **Since 1988, annual consumptive uses in the Upper Basin, less CRSP ‘net’ reservoir evaporation, have not increased.** Because reservoir storage in the CRSP reservoirs has declined since 2000 due to the millennium drought, there has been a downward trend in total consumptive use due to decreasing net CRSP reservoir evaporation.

During the period between 1988 and 2018, total consumptive uses in the Upper Basin, which includes a small portion of Arizona upstream from Lee Ferry, averaged 4.40 maf/year, including

0.540 maf/year for CRSP reservoir evaporation. The Consumptive Uses Report uses net evaporation, which is the total evaporation less the estimated natural losses from the stream surface and adjacent vegetation had the reservoir not been built (Wang and Schmidt, 2020). The Upper Basin uses are disaggregated as follows:

Upper Basin Use	**Annual Volume (maf)**
In-basin agricultural uses	2.63
Exports out of the basin	0.757
Thermal power plants	0.160
All others (domestic, in-state evap, mining/mineral)	0.312
Total Consumptive Use	3.86
Net evaporation from CRSP reservoirs	0.538
Total Consumptive and Losses	4.40

Table 2.2. Average annual Upper Basin consumptive uses and losses between 1988-2018

During the 1988-2018 period, the area of irrigated agriculture did not significantly change in the Upper Basin. There was a slight, but not significant, downward trend in transbasin exports, perhaps due to a decline in water availability at the points of diversion. There was a clear downward trend in thermal power plant use, reflecting the planned decommissioning of the Upper Basin's coal-fired thermal power plants. By sometime in the 2030s, all existing plants are expected to be shut down (Kuhn, 2020). The only subcategory which continues to project a steady increase is in-basin domestic uses. For purposes of water-supply planning, Reclamation estimates this use by multiplying the estimated population of the Upper Basin by a per capita use estimate provided by the USGS.

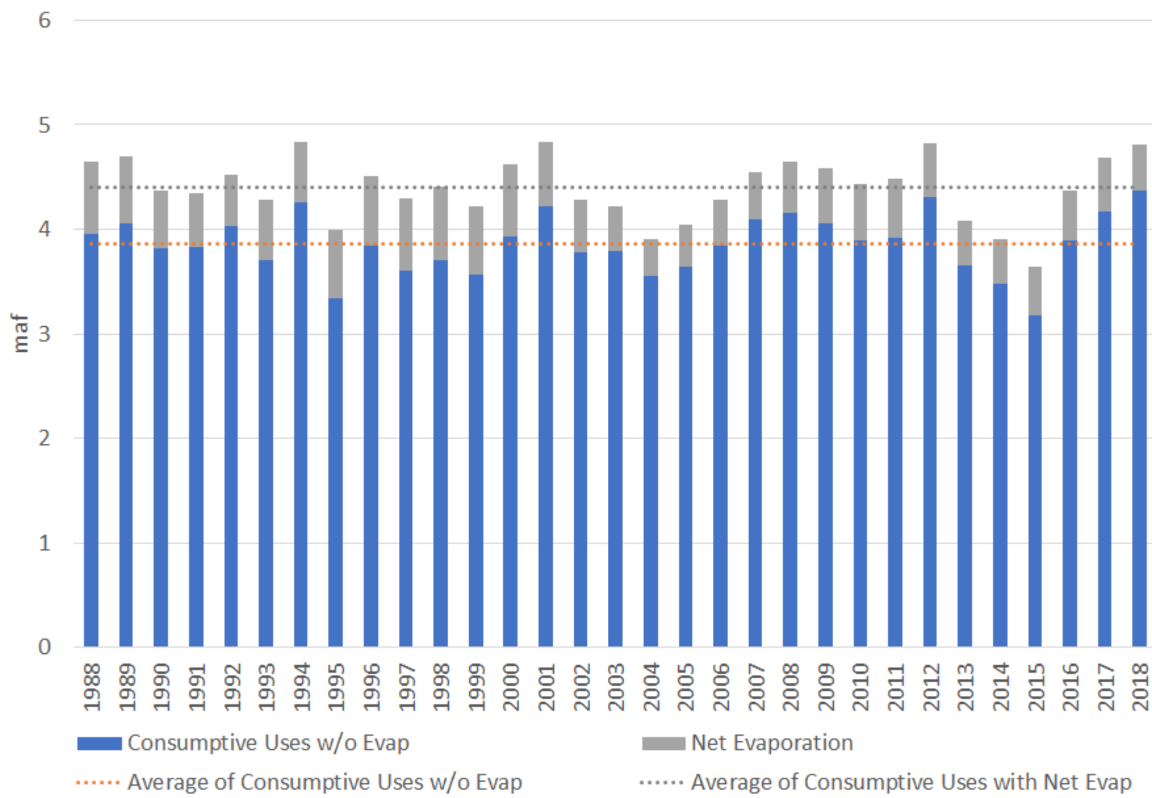

Figure 2.2 Upper Basin consumptive use with and without estimated net reservoir evaporation (1988-2018)

2.4 Aspirations and Uncertainties for the Future

Despite more than three decades of essentially constant annual uses, each of the states with an Upper Basin apportionment continues to aspire to use more water in the future (Figure 2.3 adapted from Wang et al. (2020). Since the 1980s, Reclamation and the Upper Colorado River Commission (UCRC) have estimated future water needs for the purposes of planning and policy development. This aspiration is reflected in their projections of future depletions released in 1996, 1999, 2007 and 2016. In Reclamation's 2012 Basin Study, six different assumptions of Upper Basin consumptive use were used that ranged between 5.15 and 6.28 maf/year by 2060, exclusive of potential losses associated with reservoir evaporation, phreatophyte evapotranspiration, and/or operational inefficiencies (USBR, 2012). Reclamation's analysis using each of these depletion projections estimated that total water supplies are likely to be inadequate to meet future needs.

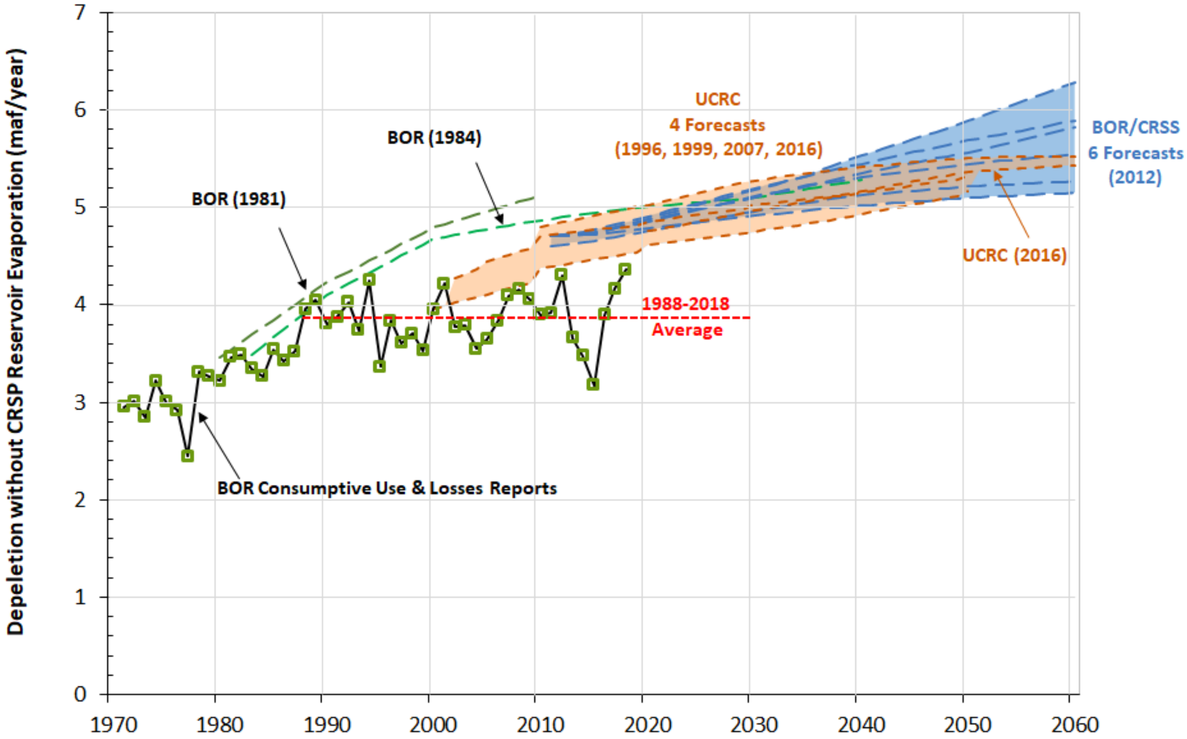

Figure 2.3. Graph showing the disparity between projections of future consumptive water use in the Upper Basin and actual use. Brown dashed lines are projections made by the UCRC in 1996, 1999, 2007 and 2016. Blue dashed lines are projections made by Reclamation in 1981, 1984, and 2012. Solid black line shows actual water use as reported by Reclamation in its semi-decadal Consumptive Uses and Losses Reports. The red dashed line shows the stable average Upper Basin Use from 1988 to 2018 (Wang et al., 2020).

The most recent projections published by the UCRC of future use (UCRC, 2016) suggest that annual depletions will increase from 4.75 maf/year in 2020 to 5.43 maf/year by 2060, plus an additional 0.520 maf/year estimated for net CRSP reservoir evaporation losses (Lake Powell, Flaming Gorge Reservoir and the Aspinall Unit). The assumptions embedded by Reclamation in the April 2020 version of the CRSS model, however, are based on depletion projections made in 2007 (UCRC, 2007) which estimate annual depletions of 5.03 maf/year in 2020 increasing to 5.52 maf/year by 2060, plus only 0.25 maf/year for 'Critical Period' CRSP evaporation losses. **It is significant that the 2007 UCRC depletion estimate for 2020 is already 1.17 maf greater than the 1988-2018 average historical uses of 3.86 maf, and 0.66 maf greater than the most recently published Upper Basin use of 4.37 maf in 2018.**

Projecting future consumptive uses in the Upper Basin is particularly difficult for several reasons:

- The apportionments to the four Upper Division states under the 1948 Compact are a percentage of the 'available water'; however the definition of 'available water' is debatable. As noted above, Article III(a) of the 1922 Compact apportions 7.5 maf/year to the Upper Basin, yet Article III(d) simultaneously requires that the States of the Upper Division must not "cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75 maf for any period of ten consecutive years." Furthermore, Article III(c) states the Upper Basin must provide half of the deficiency in meeting the 1944 Treaty obligation to Mexico, if the surplus is not sufficient. Colorado's 1948 Compact Commissioner and its first Director of the Colorado Water Conservation Board, Clifford Stone stated the following:

> "...the water available for use in the Upper Basin is that remaining after the Lee Ferry delivery requirements are satisfied. In view of the uncertainty as to the total amount of water which might be available for the Upper Basin, the Compact Commission determined that so far as the States of the Upper Division are concerned the apportionments must be in terms of percents." (Stone, 1948).

- To determine the actual water available to the individual Upper Division states, one must know both the water available upstream of Lee Ferry and the 1922 Compact obligations at Lee Ferry. The Basin States have never agreed to a consensus interpretation of the Upper Basin's obligations to Mexico under Article III(c), and climate change has made it nearly impossible to determine the reliable water available with any certainty. Thus, any depletion schedules that are designed to protect a state's future development are deeply uncertain and little more than guesses.
- For all practical purposes, the era of building new participating projects under the CRSP Act has ended. Construction is now largely complete on all the participating projects that have been authorized. While it is theoretically possible that Congress could authorize new projects, the last time this happened was 1968. Absent a source of subsidies, it is unlikely that new lands in the Upper Basin will be irrigated. An unknown dimension is the impact that rising temperatures due to climate change will have on the consumptive use of water on existing lands. The Colorado River Basin Study Technical Appendix C15, 2012, concludes that as regional temperatures rise, crop irrigation requirements will increase. The net impact on total annual consumptive uses in the Upper Basin is, however, more complicated. For total consumptive uses to increase, more water for diversion must be available.
- A few new non-federal export projects are being planned, but they are controversial, extremely expensive, and difficult to permit—such as Utah's Lake Powell Pipeline. The last new export project to be built in Colorado was the Windy Gap Project, which was completed in 1985.
- While operators of existing export projects may implement new efforts to increase the yield at the margins (firming projects), this yield is limited by the physical water available and the bypass flow requirements at the diversion points. Two example projects are the San Juan-Chama project (which diverts water in Colorado for use in New Mexico) and the Fryingpan-Arkansas project in Colorado. If climate change reduces the water available for diversion, the yield of these projects will decrease.
- National and regional economic forces are also reducing Upper Basin depletions. All of the Upper Basin's coal-fired power plants are now scheduled to be decommissioned in the next 10 to 20 years. These closings could reduce Upper Basin uses by an average

of 160,000 acre-feet/year. Much of the municipal development on the Western Slope of Colorado is occurring on previously irrigated lands. Recent studies show that the urbanization of irrigated lands reduces the overall consumptive use associated with those lands (USBR, 2018).
- The Upper Basin's Native American communities have senior water rights that have not yet been fully quantified or developed.

In summary, given the significant legal and climate change related uncertainties, planning studies should be conducted over a range of reasonable future depletion projections.

3. Current Governance and Rationale for Alternative Management Paradigms

Today, management of the Colorado River is primarily controlled by the Secretary of the Interior through the Bureau of Reclamation, who is the water master of the Lower Basin. All of the large dams are operated by the Bureau of Reclamation, and water storage and reservoir release decisions are made to implement the *Law of the River*, primarily concerning the allocation of water supply among the Basin States and Mexico. Reclamation also coordinates most efforts to revise aspects of the *Law of the River*. Western Area Power Administration makes recommendations concerning how reservoir releases might be scheduled to meet regional demands for hydroelectricity. The Secretary inevitably arbitrates among the additional recommendations of the U.S. Fish and Wildlife Service, National Park Service, Bureau of Land Management, U.S. Geological Survey (USGS), Bureau of Indian Affairs, U.S. Forest Service, and International Boundary and Water Commission (IBWC). The latter two agencies are not within the Department of the Interior.

The U.S. Fish and Wildlife Service focuses on implementation of the Endangered Species Act. The National Park Service manages lands bordering the Colorado River between Canyonlands National Park and Lake Mohave reservoir as well as other lands in the watershed, and the Bureau of Land Management administers various lands that border the river and its headwater branches. The USGS has no management responsibility but plays an important role in measuring the streamflow and fine sediment flux, as well as measuring other water quality and geomorphic parameters in parts of the channel network. Additionally, the USGS leads the Grand Canyon Monitoring and Research Center which is the primary provider of science to the Glen Canyon Dam Adaptive Management Program. The Bureau of Indian Affairs sometimes represents the interests of Native American tribes, although the individual tribes represent themselves in many circumstances. The IBWC leads formal conversations with the government of Mexico on transboundary water issues. The Secretary of the Interior has traditionally consulted with state water agencies whose primary focus has been on water supply, and the opinions and perspective of these states have substantial influence.

Secretarial decisions have included formal consultation with an expanded group of non-agency stakeholders, including the basin's Native American tribes, NGOs, the academic community, recreation interests, and smaller water agencies. Environmental considerations in many parts of the Colorado River network are conducted or advised by multi-party adaptive management programs including: the Upper Colorado River Endangered Fish Recovery Program, the San

Juan River Recovery Implementation Program, the Glen Canyon Dam Adaptive Management Program, and the Lower Colorado River Multi-Species Conservation Program. Each of these programs is a formal partnership among various federal agencies, the relevant state governments, NGOs, and other organizations who represent water-supply or hydroelectricity users. However, none of these adaptive management programs has traditionally been involved in water-supply management decisions. Most NGOs and other non-government stakeholders primarily affect the water-supply negotiation process by their influence on government agencies, commenting on Environmental Impact Statements, or litigation.

As a result of the complex institutional landscape on the Colorado River, most public policy developments regarding water management proceeds in small, incremental steps and environmental dimensions are typically detached from major water supply decisions. The institutional complexity resulting from the evolution of the Law of the River and subsequent management actions has resulted in a perceived ***path dependency***, suggesting that policies and institutions can only be altered in incremental ways and not in substantial ways. However, this perception of path dependency is misguided and potentially dangerous if existing policies and institutions are not sufficiently adaptive to respond to rapidly changing hydrologic, demographic, or economic conditions as suggested in Reclamation's 2012 Basin Study (USBR, 2012). **New approaches that are responsive to significantly drier climate conditions and changing patterns of consumptive uses may require bolder policy initiatives that exceed the incremental approach of modern management.** It is critical to explore alternative water management strategies that may extend beyond the framework of the *Law of the River* as presently interpreted.

The purpose of the Future of the Colorado River project is to develop and examine river management paradigms that may extend beyond these present institutional constructs, thereby encouraging broad conversations about future management of the Colorado River. We believe that water managers may be willing to consider a wider range of options for how the river should be managed in the future. Our project represents one way that new management strategies might be developed and encourage future discussion.

In considering different ways to manage the Colorado River system, we distinguish the following:

- We use the term *alternative management paradigms* (AMP) to mean new management paradigms that may require legal or institutional adaptations to the *status quo*. Each alternative paradigm potentially introduces a cascade of smaller scale adaptations to water management decisions that need to be described, modeled, and evaluated.
- We use the term *management variations* to mean minor variations to the current management paradigms or to the alternative management paradigms that we broadly define. This may be variations of particular variables such as pool elevations that trigger particular actions, but the general concepts and operational logic are the same.
- We use the term *scenarios* to mean 'future states of the world,' such as future runoff under different projected climate conditions and water use demand patterns.

Our goal is to present a wide range of alternative management paradigms that encourage conversation and debate about how Colorado River management could be fundamentally improved. We seek to shed the myopia of excluding potentially viable solutions that some may dismiss as impossible to implement or which might be 'radical.' In this report, we present alternative management paradigms that extend beyond the range typically considered by government agencies. We believe that institutions, including those concerned with water-supply management, evolve and the misperceptions of path dependencies established by institutions must be confronted to cope with a deeply uncertain future (Wang et al., 2020). What might seem to be a radical idea today may not be viewed as such given the current projections described in this report and elsewhere.

After presenting this wide-ranging list of alternative management paradigms, we analyze some of these alternatives in detail. Our criteria for detailed analysis was based on identifying alternatives that:

- could be precisely described and evaluated;
- are not likely to be evaluated by Reclamation in initial exploratory analyses;
- have the potential to highlight tradeoffs between meeting water supply goals and river ecosystem goals;
- have the potential to provoke thoughtful discussion among stakeholders;
- might be considered in the next round of negotiation of the Interim Guidelines;
- might be considered in the next 50 years; and/or,
- might be consistent with the perspective of non-traditional or historically marginalized stakeholders.

Clearly, further analysis of each alternative paradigm is possible, and those that are not analyzed in this paper should be considered by subsequent studies.

4. Alternative Management Paradigms for the Colorado River

In this section, we provide a ‘brainstorm’ list of alternative management paradigms (AMPs) of how the Colorado River might be managed in the future. The alternatives described here are organized into three broad categories—(I) modification of the allocation and accounting of consumptive uses and water supply; (II) modification of the operations of dams and diversions; and (III) modification of the infrastructure itself.

The alternative management paradigms described here concern changes in water-supply allocation and/or management, and have the potential for improved outcomes with respect to efficiency or environmental outcomes. In a general sense, these strategies concern management of water at a time scale of decades, years, or months. Other strategies exist or could be envisaged that specify river management at finer temporal resolution, such as days or hours, to mitigate adverse impacts of infrastructure or current water supply management. Some of these finer scale management actions, such as controlled floods, pulsed releases, reduced hydropower fluctuations, and elimination of hydropeaking on weekends, have already been considered or implemented (Schmidt, Bruckerhoff et al., in prep). In the list described below, we do not discuss these short time frame adjustments in flow, called designer flows, but we do consider alternative paradigms that could allow greater flexibility in designing and implementing such flows.

Table 4.1 summarizes the list of alternative management paradigms, with more detailed descriptions provided below. Section 5 references this table when describing the utility of current modeling tools, and alternatives marked with an asterisk (*) are examined in further detail in Section 9.

		Possible in CRSS	**Possible Using RiverWare**
I. Change rules of water-supply allocation and/or water-supply accounting			
A	*Determine shortage or surplus conditions based on combined reservoir storage	Yes	
B	Change the location of the dividing point between the Upper and Lower Basin	Yes	
C	Establish Basinwide Water-Supply Accounting	No	Yes
D	Establish Open Markets	No	No
E	Adjudicate Tribal Water Rights and Give Tribes Control	No	Yes
F	Adaptive Drought Contingency Plans	Yes	
II. Change operations of existing infrastructure: mainstem Colorado River			
A	*Fill Mead First	Yes	
B	*Fill Powell First	Yes	
C	Minimum Lake Powell Storage for ‘Designer Flow’ Releases	Partially	
D	*Grand Canyon Engineered Flood Flows	Partially	
E	Grand Canyon Engineered Low Flows	Partially	
F	Powell-Mead Adaptive Environmental Integration	Partially	

G	Lower Basin Adaptive Environmental Integration	Partially	
H	Hydropower - Renewable Integration	No	Partially
III. Change operations of existing infrastructure: headwater branches			
A	*Flaming Gorge to Powell Backup	Yes	
B	Maintain Water Storage in Flaming Gorge to Ensure Designer Flow Releases	Partially	
C	Flaming Gorge Engineered Flood Flows	Yes	
D	San Juan Habitat Enhancement	Partially	
IV. Modify infrastructure			
A	Construct mitigation infrastructures at dams to increase fine sediment transport	No	
B	Construct infrastructures at dams to eliminate adverse temperature conditions	No	Partially
C	Construct turbines on the river outlets at Glen Canyon Dam	No	
D	Opening River Diversion Tunnels of Glen Canyon Dam	Yes	
E	Increase Release Capacity of Flaming Gorge	Yes	
F	Construct New Diversions that Increase Upper Basin Consumptive Uses	Yes	

* Indicates alternatives management policies examined in further modeling detail in Section 9 of this study

Table 4.1. Brainstorm list of some alternative management paradigms, indicating the current ability of the CRSS and/or RiverWare software to analyze the implications of each alternative. ‘Partially’ indicates cases where there is a usefulness at the spatial and temporal scale of the model, but additional modeling might be required for constituents of interest (e.g. sediment), a finer scale of analysis might be complementary, or nuances of the proposal would determine the extent of usefulness of these tools to evaluate their efficacy.

I. Change rules of water-supply allocation and/or water-supply accounting

A) Determine shortage or surplus conditions based on the combined reservoir storage of Lake Powell and Lake Mead

This alternative would consider the combined water storage of Lake Mead and Lake Powell as the primary metric to determine water supply conditions (i.e., shortage or surplus conditions) in the Colorado River Basin. This paradigm would provide an alternative to the framework developed during the 2007 Interim Guidelines that defined shortage or surplus conditions based on reservoir elevation of Lake Mead. Except for evaporation and seepage losses, all water entering Lake Powell is eventually delivered to Lake Mead and the Lower Basin, and 92% of all water that flows into Lake Mead comes from Lake Powell (Wang and Schmidt, 2020). This alternative recognizes the reality of the hydrography of the basin and would remove the institutional constraints that currently govern releases from Lake Powell. One implication of this alternative is to potentially allow alternative management strategies of river flow in the Grand Canyon that would achieve substantially different river ecosystem outcomes.

B) Change the location of the dividing point between the Upper and Lower Basin

This alternative would change the location for Compact water deliveries from the Upper Basin to the Lower Basin (i.e. the Compact Point) from Lee Ferry to Hoover Dam. Physically, the two reservoirs are separated by a long bedrock channel with no extractions and 800,000 acre-feet/year of additional inflows (Wang and Schmidt, 2020), therefore, the Powell/Grand Canyon/Mead part of the basin effectively is one large storage system. However the current location of the political division discourages integrated reservoir management. Moving this location would eliminate the artificial administrative distinction that releases from Glen Canyon Dam represent transfers of water from one basin to the other. Such a strategy could be implemented in concert with a change in the distribution of reservoir storage in Lake Mead and Lake Powell to improve efficiency or ecosystem conditions. Institutional challenges to this alternative would include the uncertainty in how to consider Nevada's major diversion as either an Upper Basin or a Lower Basin diversion, and how to consider Arizona's development of the Little Colorado River, which is a tributary that enters the Colorado River upstream from Lake Mead.

C) Establish Basinwide Water-Supply Accounting

This alternative would establish a water-supply accounting system that would track consumptive uses in the Upper Basin, Lower Basin, and in Mexico. This system would track and account for annual volumes allocated to each water user so that water not used in any year could be stored in one or more of the major reservoirs of the system. Different schemes of defining water users could be considered; thus, the level of aggregation of water uses might occur on a state level or at the level of individual water districts. Specification of the annual volumes deposited by each water-use entity would *be derived from various historical elements of the Law of the River and any forthcoming revisions to the 2007 Interim Guidelines. This system would consider all consumptive users of water in the basin including municipalities, irrigation districts, and Native American tribes in the U.S. or Mexico. This paradigm would differ from the Intentionally Created Surplus mechanism (2007 Interim Guidelines) or the Intentionally Created Mexican Apportionment mechanism (Minute 319 and Minute 323) which considered voluntary banking to encourage conservation of small volumes of water and thereby marginally increase resilience. By allowing any user in the basin to voluntarily bank larger volumes of waters in one or more reservoirs, greater flexibility of water exchanges and market mechanisms can be introduced into Colorado River management.*

D) Establish Open Markets

This alternative would allow the temporary or permanent exchange of water rights throughout the basin based on market mechanisms. This alternative would encourage reallocation of water use rights based on economic drivers including productivity of use and valuation of increasingly scarce water resources. Exchanges of water could be considered at various spatial scales: within either or both the Upper Basin or Lower Basin, across all state lines, or across international boundaries. This alternative might be associated with elimination of consumptive water use allocations between the Lower and Upper Basin, and might effectively re-allocate water-supply to the highest economic use, subject to physical distribution limitations and negotiable regulations concerning equity and environmental implications of the exchanges.

E) Adjudicate Tribal Water Rights and Give Tribes Control of Those Adjudicated Rights

This alternative would adjudicate unresolved water rights held by U.S. Indian tribes and allow these Tribes to control, store, utilize, and allocate those rights. This alternative could be implemented along with establishing markets that would allow tribal water rights to be traded throughout the Colorado River Basin.

F) Adaptive Drought Contingency Plans

This alternative aims to adaptively manage basinwide consumptive uses with new and evolving information that emerges as droughts occur and climate implications unfold. Salehabadi et al. (2020) provided plausible estimates of what may occur in the future based on resampling from the most extreme past droughts. While this is critical for planning purposes, it is important to recognize, especially given climate change, that "stationarity is dead" (Milly et al., 2008) and that it is insufficient to base future planning on past flows alone. Milly and Dunne (2020) and Woodhouse et al. (2021) are just the latest among many researchers who offer models that estimate streamflow sensitivity to climate change. Recognizing the already over-allocated status of the river, adaptive contingency planning accepts the fundamental uncertainties associated with future water availability through the proactive preparation of multiple drought contingency plans with different Upper and Lower Basin demand contributions that seek system-wide *sustainability at a range of expected inflows. Selection and application of plans could consider weighting more recent hydrologic conditions as more probable, re-evaluating the most recent uses and their potential to implement conservation measures, thus continuously adapting management to evolving conditions.*

II. Change operations of existing infrastructure: mainstem Colorado River downstream from Green River confluence

A) *Fill Mead First*

First proposed by the Glen Canyon Institute in 2009, the concept of Fill Mead First (FMF) suggests that Lake Mead would be operated as the primary main-stem water storage facility. The potential advantages of this proposal to water supply would be to reduce evaporation losses by reducing the ratio of reservoir surface area to storage volume by concentrating reservoir storage in one facility. The primary ecosystem implication of this proposal would be the return of upstream parts of Lake Powell from reservoir to river ecosystems, especially in parts of Cataract Canyon and the San Juan River Canyon. Power production would be concentrated at Hoover Dam and require renegotiation of contracts that allocate the distribution of federally subsidized hydropower.

The original proposal by the Glen Canyon Institute included three phases of implementation. In Phase One, Lake Powell storage would be reduced to an elevation just higher than that necessary to produce hydroelectricity (i.e., minimum power pool). In Phase Two, Lake Powell storage would be reduced to just above dead pool, and water could only be released through the river outlets. In Phase Three, the river diversion tunnels would be reopened, and Glen Canyon Dam would be entirely bypassed. Some of the implications to evaporation and seepage losses were analyzed by Schmidt et al. (2016), but a detailed strategy of implementation of this proposal was never delineated, in light of future hydrologic uncertainties. In subsequent sections of this report, we analyze the implications of select variations of the Fill Mead First proposal that allow Lake Powell to fall to the river outlet intakes (similar to Phase Two, but with greater specificity and analysis that has not been previously conducted). The implementation of Phase Three is being evaluated elsewhere and would seek to return a relatively natural streamflow and temperature regime to the Colorado River in the Grand Canyon. There are many known challenges in the implementation of this proposal (Schmidt et al., 2016), such as the risk of scouring the sediments of the Grand Canyon if large water releases devoid of fine sediment are discharged using existing water release infrastructure at Glen Canyon Dam (i.e. Phase One and Phase Two). In contrast, reopening river diversion tunnels might evacuate fine sediment from parts of Lake Powell and potentially deliver very large amounts of fine sediment to the Grand Canyon (Phase Three).

B) *Fill Powell First*

The concept of Fill Powell First (FPF) is the antithesis to the Fill Mead First proposal and is derived from standard engineering practice of reservoirs—retaining the maximum volume of water in upstream reservoirs and allowing downstream reservoirs to fluctuate to meet immediate needs of water users (Lund and Guzman, 1999; Sheer and Foundation, 2014). Similar to the FMF approach, the potential water-supply advantage of this alternative is to reduce evaporation losses by concentrating storage in one facility. The FPF paradigm has additional advantages relative to FMF of maintaining water higher in the watershed for more flexible power generation through both reservoirs and maintaining space in Lake Mead to readily capture intervening flows. With a full Lake Powell, releases from Glen Canyon Dam would more often be cool in summer, which might provide advantage to the non-native recreational trout community, but would be likely to disadvantage native fish. In addition, reduced Lake Mead reservoir elevations would more likely leave Pearce Ferry Rapid exposed, which is located 40 river miles downstream from the inflow to the reservoir. This rapid may act as an impediment to upstream migration of non-native reservoir fish into the Grand Canyon, but this effect is currently poorly understood. Seepage losses might increase with storage in Lake Powell where the surrounding bedrock in the permeable Navajo sandstone (Schmidt et al., 2016) and power production would be concentrated at Glen Canyon Dam.

C) *Maintain minimum Lake Powell Storage for 'Designer Flow' Releases into the Grand Canyon*

This alternative management paradigm proposes that a minimum water storage in Lake Powell be maintained to allow sufficient flexibility to implement 'designer flows,' with a goal to maintain sandbars and enhance the aquatic and riparian ecosystem of the Grand Canyon. These designer flows—controlled floods and macroinvertebrate production flows—typically have durations of days and do not affect the total amount of water released from the Upper Basin to the Lower Basin. Implementation depends on adequate reservoir storage flexibility in how water is released throughout the year, and release of controlled floods requires use of the full capacity of the Glen Canyon Dam power plant and the capacity of the river outlets. Although there is no minimum water storage in Lake Powell established below which these flows cannot be implemented, designer flows may be less likely to be implemented during periods of declining water storage. Experimental release flows conducted since 1996 have achieved some degree of success in maintaining sand bars and increasing the food base of the aquatic ecosystem. This alternative management paradigm seeks to expand upon these successful experimental policies.

D) *Grand Canyon Engineered Flood Flows*

The concept of Engineered Flood Flows (EFFs) is to use the existing infrastructure—Glen Canyon Dam and Lake Powell—to simulate natural hydrologic conditions in the Grand Canyon to the best of the ability of the existing water release facilities of the dam. This alternative could be implemented in various ways, requiring anywhere from minimal to substantial adaptations to the Law of the River. This alternative assumes that a *somewhat natural flow regime, which attempts to match the historical timing of peak flows, is environmentally preferential even if the magnitudes of those peak flows are suppressed relative to historical conditions. A minimal implementation of the alternative management paradigm would be to maintain the current coordinated operations between Lake Powell and Lake Mead, and only adapt the monthly distribution of releases. This alternative could also be implemented in concert with any other coordination strategy that specifies annual releases from Glen Canyon Dam. Due to the risk of undesirable erosion of fine sediment in the Grand Canyon, this alternative would require implementation of a complementary sediment augmentation strategy.*

E) *Grand Canyon Engineered Low Flows*

The focus of Engineered Low Flows (ELFs) in the Grand Canyon is to reduce flows below current minimum discharges to help restore particular components of the pre-dam condition, which is currently marked by large extents of bare sediment and a paucity of riparian vegetation. In addition to the notable loss of pre-dam floods driven by snowmelt in the Upper Basin, the operation of Glen Canyon Dam for downstream water delivery and hydropower production has resulted in the elimination of historic summer and fall low flows in the Grand Canyon, hence base flows have increased in the post-dam period. This has resulted in reduced areal exposure of bare sediment and widespread colonization of the riparian zone by novel vegetation communities along the river. As with engineered flood flows, the re-introduction of low flows through Grand Canyon may require adaptations to the Law of the River, or an increase in release volumes outside of periods of low flows to offset reduced downstream water delivery during these periods. However, no modifications would be required to the infrastructure of Glen Canyon Dam to achieve modern-day low flows consistent with their pre-dam counterparts, nor would sediment augmentation be necessary. Reducing the magnitude of low flows in the Grand Canyon might have significant impacts to river navigation by large motorized rafts.

F) *Powell-Mead Adaptive Environmental Integration*

The concept for this alternative is to allow maximum flexibility in the operation of Glen Canyon Dam to enhance ecosystem outcomes in the Grand Canyon by explicitly ***not*** *specifying operations based on pre-existing institutional criteria. This alternative would treat Lake Powell and Lake Mead as a fully integrated system that would 1) pass water to users in the Lower Basin and Mexico with a similar reliability as is currently enjoyed, and 2) allow the movement of water through the Grand Canyon to be continuously adapted based on dynamic ecosystem needs. These needs would depend on factors such as desired water temperatures to maximize growth or minimize harm to fish populations, fall and spring High Flow Experiments (HFEs) that seek to rebuild sand bars, predicated upon sufficient antecedent sediment delivery from tributaries, and releases to support trout and/or macroinvertebrate populations. In essence, this alternative would allow continuous adaptive management of Lake Powell releases based on scientifically demonstrated needs of the Grand Canyon ecosystem. Additionally, this* *alternative might include intentional mixing of releases from the powerplant and river outlets to control the temperature of reservoir releases.*

G) *Lower Basin Adaptive Environmental Integration*

Similar to the Powell-Mead Adaptive Integration (Alternative II.E), this alternative would allow additional releases from Lake Mead, which would be passed through Lakes Mohave and Havasu to better sustain ecosystems in the Lower Basin, the Delta, and the Salton Sea, including seasonal or periodic flood flows. The proposed approach is to quantify and manage an annual volume in Lake Mead for meeting downstream environmental objectives in the Lower Basin. This annual volume could be held constant or adapted over time based on hydrologic conditions. This alternative might include strategic reservoir operations, such as improved management of lake levels in Lake Mohave for spawning of endangered fish species (i.e. Razorback Sucker) and be operated in concert with a basinwide accounting system (Alternative I.C) or markets (Alternative I.D).

H) *Hydropower—Renewable Integration*

The concept of this alternative is to adapt hourly, daily, and monthly releases from the major Colorado River mainstem reservoirs to allow hydropower generation to smooth production from, and thus enhance the transition to, alternative energy sources. The growing presence and contribution of wind and solar energy to national electrical grids will cause an increasing stochasticity of hydropower supply, which will result in an increasing demand for energy storage. Operating one or potentially several of the large hydropower facilities in close conjunction with these increasing alternative supplies can provide this energy storage. Co-locating large wind and solar generation fields close to hydropower facilities can allow these alternative sources to add to the distribution networks to minimize the need for supply grid expansion.

III. Change operations of existing infrastructure: headwater branches (upper Colorado, Green, and San Juan River watersheds)

A) Flaming Gorge to Powell Backup

The objective of this alternative is to use the storage in Flaming Gorge reservoir to supplement Lake Powell water storage during times of significant drought, even if such supplementation would result in draining of Flaming Gorge reservoir. This strategy would significantly expand upon provisions in the Drought Contingency Plan that increase releases from Flaming Gorge under a limited set of conditions. This alternative is sometimes called Extended Operations of Flaming Gorge reservoir.

B) Maintain Water Storage in Flaming Gorge to Ensure Designer Flow Releases into the Green River

This alternative would identify an annual storage volume in Flaming Gorge reservoir to be released at the discretion of the Flaming Gorge Technical Working Group and the Upper Colorado River Endangered Fish Recovery Program to meet downstream environmental needs. These 'designer flows' from Flaming Gorge Dam would be designated for management of the fish community of the Green River. Peak spring releases that provide access to floodplain habitats would be timed to match the presence of larval Razorback Suckers (LaGory et al., 2012). Similarly, short duration (approximately three days) high releases that occur before Colorado pikeminnow larval drift occurs could disrupt smallmouth bass nests, a non-native predator that consumes native species on the Green River. These designer flows require that sufficient water storage in Flaming Gorge is maintained so that adequate releases can be made based on regular evaluations of the aquatic and riparian ecosystem of the Green River in Dinosaur National Monument and elsewhere on the Green River.

C) *Flaming Gorge Engineered Flood Flows*

This alternative would provide regular releases from Flaming Gorge Dam to meet environmental objectives in the Green River within the hydraulic limitations of the dam outlet works. Furthermore, this could occur in conjunction with Alternative IV.D (Increase Release Capacity of Glen Canyon Dam by Opening River Diversion Tunnels) to allow a wider range of potential release patterns. Peak flow recommendations defined by magnitude, duration, and timing of reservoir releases would be established for normal operations and adapted for annual hydrologic conditions. In contrast to severe sediment deficit conditions in Grand Canyon identified in other alternative management paradigms, implementation of this alternative would exacerbate sediment deficit conditions only in the 64 river miles between the Flaming Gorge and the Yampa River confluence due to the large natural inputs of fine sediment that are available from the Yampa River and other tributaries.

D) *San Juan Habitat Enhancement*

The purpose of this alternative is to adapt the operation of Navajo Dam in such a way that the habitat for endangered Colorado pikeminnow and razorback sucker are optimally safeguarded or enhanced. Currently, high flow releases on the San Juan are limited to approximately 12,500 ft^3/s due to human settlement and activity on the floodplain. This alternative proposes occasional high flow events more similar to historic levels (greater than 15,000 ft^3/s) to improve floodplain habitat for razorback sucker and Colorado pikeminnow recruitment. However, this alternative would require close cooperation with downstream users and communities. Implementing high flow events assumes this would be beneficial for floodplain habitats despite years of geomorphic change and alteration of sediment dynamics. In years in which high flow events are not possible, holding water back to promote retention of larvae is hypothesized to benefit razorback sucker, while allowing more water to be stored for subsequent years. Frequent occurrence of low-flow events, though, have the potential to adversely affect Colorado pikeminnow and benefit non-native species (Gido and Propst, 2012).

IV. Modify infrastructure

A) *Construct mitigation infrastructures at dams to increase fine sediment transport*

This alternative seeks to eliminate one of the major impediments to restoring the native ecosystems of the Colorado River—trapping of fine sediment in large reservoirs—by implementing various infrastructure modifications to the dams of the Colorado River. Reservoirs that trap significant amounts of sediment release clear water, which perturbs downstream river systems into sediment deficit. As a result, the duration and magnitude of controlled flood releases from Lake Powell is limited to avoid adverse erosion, and the HFE Protocol is based on the very small supply of sediment delivered to the post-dam river by the Paria River. To facilitate increased sediment supply, infrastructure options include routing sediment-laden flows through or around the storage pools, removing deposited sediment following deposition, or importing sediment from alternative sources (Morris, 2020). Randle et al. (2007) estimated that it would cost between $200 and $400 million in initial capital costs to construct a pipeline and dredge fine sediments to transfer them from the mouth of Navajo Canyon around Glen Canyon Dam and into the Colorado River downstream. This does not necessarily change the movement of water through the channel network, but does allow further restoration efforts to occur.

B) *Construct mitigation infrastructures at dams to eliminate adverse downstream temperature conditions*

This alternative seeks to mitigate the effects of altered temperatures on ecosystems downstream of dams by mixing deep and shallow reservoir water, analogous to the selective withdrawal system in place at Flaming Gorge Dam on the Green River. This would allow managers to warm the downstream river when Lake Powell was relatively full and to cool releases when Lake Powell was relatively empty. In either case, the opportunity to design temperatures of reservoir release rather than to simply accept those temperatures as solely dependent on reservoir storage might increase the opportunity for better management of the aquatic ecosystem of the Grand Canyon. Furthermore, improving temperature conditions would also have implications for nutrients in some years.

C) *Construct turbines on the river outlets at Glen Canyon Dam*

This alternative would allow hydroelectricity to be produced when the river outlets are used at Glen Canyon Dam. This would potentially eliminate energy generation losses when making releases for controlled floods through the Grand Canyon, which is currently considered one of the adverse effects of large releases for environmental purposes. Implementation of this alternative would also allow power to be produced when reservoir storage levels have greatly declined, since reservoir water enters the river outlets more than 100 ft below the elevation of the lowest turbine intake. Furthermore, this would allow for the release of colder, more nutrient rich water during *certain times of the year because lower-temperature water could be drawn from this deeper portion of the reservoir.*

D) *Increase Release Capacity of Glen Canyon Dam by Opening River Diversion Tunnels*

The purpose of this alternative is to allow water to bypass Glen Canyon Dam at very low reservoir levels, thus eliminating the 'dead pool' in Lake Powell (i.e., when water in the reservoir is below the river outlet works and cannot be released downstream) and also to introduce a mechanism to directly pass sediment from the reservoir into Glen and Grand Canyons downstream. The diversion tunnels originally cut through the sandstone walls of Glen Canyon could be re-drilled or alternative tunnels could be constructed to allow large sediment-laden flows to be discharged downstream. However, it is unclear how rapidly sediment would pass downstream of Glen Canyon Dam because the majority of sediment has accumulated at the head of Lake Powell in the lower reaches of Cataract Canyon, more than 180 mi upstream from Glen Canyon Dam.

E) *Increase Release Capacity of Flaming Gorge*

The purpose of increasing the release capacity of the Flaming Gorge Dam is to allow for a more natural flow regime in the Green River. Current operations seek to match the timing of hydrologic conditions with the Yampa River to enhance habitat downstream of the confluence of these rivers, which would be less critical with additional flexibility in Flaming Gorge releases.

F) *Construct New Diversions that Increase Upper Basin Consumptive Uses*

This alternative would focus on construction of new facilities, including expansion of dams in the headwaters of the upper Colorado River (e.g., Gross Point Dam) and construction of the Lake Powell Pipeline. The Lake Powell Pipeline would provide a secondary water supply to Washington County, Utah, and represents the most significant new consumptive use of Colorado River water that is being considered today. Any new Upper Basin project includes benefits and risks to water users in the Lower Basin, as well as the Upper Basin. Robust analyses of changes in the risk of increased Compact curtailments would be critical.

Some of the alternatives described above are evaluated using adaptations to the CRSS model and described in subsequent sections to this report. Other tools however might be more appropriate for evaluating particular alternatives and are being evaluated in on-going work.

Part 2. Evaluating Alternative Management Paradigms

The following sections describe the analyses of some of the alternative management paradigms described in Section 4. The general methods and approach used to conduct the analyses are explained in Section 5. Assumptions about future hydrologic runoff to evaluate alternative management paradigms within the modeling framework are described in Section 6. Assumptions and approaches for considering future Upper Basin depletions are described in Section 7. The metrics we used to compare alternative management paradigms are presented in Section 8. Finally, Section 9 presents the outcomes of selected alternative management paradigms that were simulated using the methods and assumptions described throughout the previous sections.

The analytical approach that we follow—establish general methods, define hydrologic scenarios, define assumptions regarding Upper and Lower Basin depletions, define performance metrics to be used in comparing alternatives, and compare performance—is an approach that can be used with any suggested management paradigm. One of our objectives here is to demonstrate the cascade of considerations that must be addressed if one is to transform a vague notion into a rigorously defined alternative that can be quantitatively evaluated.

5. Methodological Approach

5.1 The Colorado River Simulation System (CRSS)

We used the Colorado River Simulation System (hereafter 'the CRSS model' or simply 'CRSS') to explore different strategies for managing the Colorado River and its headwater branches. In the 1970s, the Bureau of Reclamation began to develop computer code and models using the FORTRAN programming language, which became known as the CRSS by the early 1980s. In the 1990s, CRSS was transferred to the generalized RiverWare software (Zagona et al., 2001; Fulp et al., 1999). Today, it remains the single most comprehensive representation of the elements of the *Law of the River*, with strengths and limitations described by Alexander et al. (2013) and Wheeler et al. (2019). The CRSS model is maintained and updated several times each year by Reclamation and is made available to stakeholders through a Stakeholder Modeling Work Group. Throughout its continuous development, CRSS has been used to evaluate federal/state water policy, develop strategies to confront declining runoff and increasing demand, evaluate alternatives for Environmental Impact Assessments, and inform negotiations of bi-national agreements.

Reclamation's goal is that CRSS be available, useful, and accepted by stakeholders of the Colorado River. Because use of CRSS requires expertise in the RiverWare modeling framework, many state and regional water agencies employ technically trained staff to run CRSS. Other organizations use CRSS by employing consulting services that provide technical assistance. Reclamation actively encourages members of the Stakeholder Modeling Work Group to use CRSS to conduct their own studies by making adaptations to the model. Our study implements several significant modifications to the April 2020 version of the CRSS model released by Reclamation on May 11, 2020.

Many assumptions are embedded in the CRSS model provided by Reclamation, yet the structure allows these assumptions to be adaptable to simulate alternative futures. Examples of these assumptions include future hydrologic conditions, schedules of future depletions, operational rules to store and release water from reservoirs to meet the various downstream uses, change to the prioritization of water uses, and changes to the properties of infrastructure. Certain management policies are not explicitly considered in the CRSS model such as how High Flow Experiments (HFEs) are conducted in the Grand Canyon. Other important policies are not precisely simulated in CRSS due to conflicting views on the *Law of the River*, such as how the Colorado River Compact might be administered given disagreements between the Upper and Lower Basin States regarding interpretation of the Compact, particularly regarding the magnitude of the required 10-year delivery from the Upper to the Lower Basin. While the CRSS model seeks to reflect the best interpretation of the physical system, the *Law of the River*, and future conditions, many assumptions have a high degree of uncertainty (Wang et al., 2020).

5.2 Lake Powell Release Temperature Model

To help evaluate downstream river ecosystem response to different management strategies explored by CRSS, we developed and applied a relatively simple monthly dam release temperature model. The temperature of water passed through the Glen Canyon Dam penstock intakes reflects the characteristics of water in a withdrawal zone. The thickness of this withdrawal zone is determined by stratification in the reservoir, ambient reservoir currents, forebay bathymetry, the intake geometry, and the amount of water being drawn through the intakes. The withdrawal zone tends to be higher than the penstock intake centerline elevation, and measurements made during a High Flow Experiment in 2008 when reservoir was at 3590 ft msl suggests this value is about 15 ft (Vermeyen, 2011). For this reason, the water temperature being passed through the penstock intakes may be more similar to water temperatures located at shallower depth in a temperature profile measured at some distance from the intakes. Our model assumes that the average water temperature within the withdrawal zone can be approximated for a given month and surface lake elevation using (a) a monthly average reservoir temperature profile and (b) a constant representing the difference between the depth of the penstock intakes and depth in the profile that best represents the withdrawal zone. To construct the model, we first developed monthly reservoir temperature profiles by averaging all reservoir temperature profiles reported by Vernieu (2015) for a given month. We then calculated the depth of the water withdrawal based on the difference between surface elevation and the elevation of the penstocks. For each month, we utilized a constant offset (15 ft) to add to the penstock depth to better represent the withdrawal zone. This model allowed us to efficiently predict release water temperature for each month and surface elevation from CRSS. Unlike other process-based models (e.g. CE-QUAL W2), the model used here does not capture the variability associated with tributary inflow and temperature or weather conditions. Schmidt, Bruckerhoff et al. (in prep) analyze release temperatures from Lake Powell using a more sophisticated reservoir model, and also uses a river temperature model (Mihalevich et al., 2020) to estimate the rate of downstream warming of the Colorado River in summer.

5.3 Capabilities and Limitations

The combination of the CRSS model and the empirical reservoir temperature model provides a viable method to simulate alternative management policies that focus on operations of the major reservoirs and evaluate their implications on water supplies, river flows, and downstream temperature effects. The CRSS model lends itself to evaluating changes to the operations of the Aspinall Unit, Flaming Gorge, Navajo reservoir, and Lake Powell in the Upper Basin, and Lake Mead, Lake Mohave, and Lake Havasu in the Lower Basin. The monthly time step and long-term planning focus of CRSS allows many alternative management paradigms to be readily evaluated, however, the coarse timescale limits the ability of this model to simulate sub-monthly processes that are particularly relevant for ecosystem objectives, environmental evaluations, and the implementation of designer flows (Wheeler et al., 2019). Alternatives that change the primary reservoir operations can be readily evaluated using CRSS, while evaluation of other alternatives may require an entirely new model. For example, altering the CRSS model to determine shortage or surplus conditions based on the combined reservoir storage in Lake Mead and in Lake Powell is possible by modifying the logic of CRSS, but the absence of a full accounting structure makes it unlikely that CRSS would be an appropriate tool to establish and study a basinwide water-supply accounting alternative. We note that the RiverWare software does have a full accounting structure that is not currently being used by the CRSS model.

The CRSS model can simulate some, but not all, changes to infrastructure. Simple changes to dam release capacities are possible in CRSS, however, RiverWare does not simulate sediment transport processes. Therefore, the model is not useful to analyze the increase of sediment transport and is insufficient to analyze alternative management paradigms that may significantly alter sediment transport. In this case, alternative analytical techniques must be employed. Table 4.1 indicates the possibility of the CRSS model to be used to evaluate each alternative management paradigm presented and whether the generalized RiverWare platform could be used to develop an alternative model. RiverWare does have the capability to simulate temperature processes, although the CRSS model does not utilize this functionality. Furthermore the alternatives that focus on designer flows, habitat improvement, and environmental integration can only partially be analysed with the monthly CRSS model, while other techniques would be required to analyze sub-monthly processes and effectiveness of meeting some environmental objectives. Some of these alternative approaches are discussed by Schmidt, Bruckerhoff et al. (in prep) and were previously discussed by Alexander et al. (2013).

6. Future Hydrology

Any alternative management paradigm must address the challenges presented by a warming climate and declining watershed runoff. Thus, an essential assumption associated with each CRSS model run is the assumed future hydrologic conditions. Reclamation provides the Stakeholder Modeling Work Group with input ‘hydrology sets’ that represent assumed conditions of watershed runoff at 29 inflow locations, with 20 of these locations distributed throughout the Upper Basin and 9 in the Lower Basin. Two hydrology sets, differentiated below, assume different watershed conditions, but both sets use magnitudes and sequences of annual flows developed from estimates of 'naturalized' historical conditions that have occurred in the past. These flows are estimated by Reclamation from measured flows at gages and estimates of consumptive uses and losses upstream from each gage. The advantages and challenges in development of these naturalized data are described by Wheeler et al. (2019), Fleck et al. (2019), Lukas and Payton (2020), and Salehabadi et al. (2020).

The two hydrologic data sets developed by Reclamation are derived from different time periods of the historical record, and these two periods have different average annual runoff. The first hydrologic data set, called the *Direct Natural Flow* (DNF), uses the entire 113-year record of estimated natural flows between 1906 and 2018, which notably includes the period between 1906 and 1929 called the early 20th century pluvial period when basin runoff was unusually large (Salehabadi et al., 2020). The second set of hydrologic data, called the *Stress Test* hydrology, uses a 31-year subset of flows from 1988 to 2018, which contains years of high flows as well as the millennium drought that began in 2000. When the CRSS model uses the DNF data set, it is run for 40 years projecting operations from 2021 until 2060. Applying the *Stress Test* hydrology, the model is run for a period of 31 years, projecting operations until 2051.

The Index-Sequential Method (ISM) is used to develop historically probabilistic outcomes for each of these two data sets (Kendall and Dracup, 1991; Ouarda et al., 1997) resulting in multiple hydrologic traces for each data set. Each trace uses a sequence of the estimated natural flow record starting from one of the years in the historical period. In the case of the DNF hydrology data set, the 113 years of data allow 113 individual traces based on each year as a different 'starting point' followed by the next 40 years of flows that occurred after that starting point. In the ISM method, sequences that reach the end of the record (2018) are 'wrapped' back to include data from 1906 depending on the number of additional years required to fill out each 40-year period. By using the ISM method, each modelled year into the future is simulated using all historical points in time, and each historical year is considered equally probable. One obvious limitation of the ISM approach is that an assumption is made that the sequence of future annual flows exactly matches the sequence of wet and dry years that occurred prior to 2018. As a result, no new magnitudes or sequences are tested that did not occur in the historically sampled period. The *Stress Test* hydrology set also uses the ISM method to develop 31 traces but uses a smaller sample period from 1988-2018.

We evaluated each alternative management paradigm using these two hydrology sets provided by Reclamation. In addition, new hydrology sets were developed to evaluate other hydrologic scenarios. Some of these new sets represent scenarios of hydrologic conditions with exceptionally long periods of low watershed runoff. Other hydrology sets represent scenarios of projected runoff under an increasingly warm climate. These types of scenarios are plausible futures that should be considered for planning purposes.

To evaluate periods of extended droughts, we used a resampling technique developed by Salehabadi et al. (2020) to generate sets of hydrologic traces that replicate the statistical characteristics of three periods of low runoff. In contrast to the ISM approach, the method of

Salehabadi et al. (2020) develops randomized sequences of runoff conditions. Reclamation's reconstructions of naturalized annual flows were used to develop hydrology sets based on the current Millennium Drought (2000-2018) and the mid-20th century drought (1953-1977). A third extended drought hydrology set was developed based on estimated hydrologic conditions between 1576 and 1600, derived from tree-ring analyses (Meko et al., 2017). Salehabadi et al. (2020) generated 100 traces derived from each of these three periods, which were then provided as input to the CRSS model. Because these three drought scenarios have occurred in the past, it is appropriate to evaluate the implications of their occurrence in the future. In the analyses described in subsequent parts of this report, we refer to these three hydrologic scenarios as *2000 Resample*, *1953 Resample*, and *1576 Resample*.

We also analyzed the performance of alternative management paradigms in response to anticipated effects of aridity, leading to decreasing runoff associated with a future warming climate. We applied runoff estimates developed by Udall (2020), which uses Reclamation's naturalized flow data for the period of record (e.g., 1906 to 2017) and applies uniform proportional decreases in the runoff based on an assumed relation between the amount of atmospheric warming and decreases in Colorado River runoff—i.e., a percent change in annual runoff due to a 1°C change in annual temperature. This 'new abnormal' method allows the projection of progressively declining watershed runoff into the future based on observed warming of the atmosphere (Udall and Overpeck, 2017). Temperature changes based on the Representative Concentration Pathway (RCP) 4.5 and the RCP 8.5 climate projections were used, along with assumptions of 3%, 6.5%, and 10% decreases in runoff per degree warming. In the analyses described in subsequent parts of this report, we refer to these six scenarios as *RCP 4.5_030, RCP 4.5_065, RCP 4.5_100, RCP 8.5_030, RCP 8.5_065, and RCP 8.5_100*. For each hydrology set, the ISM method was used to generate 112 individual traces.

The different hydrologic scenarios thus reflect a range of possible future conditions in the Colorado River. Figure 6.1 illustrates the range and distributions of the sum of the 20 naturalized Upper Basin inflows locations.

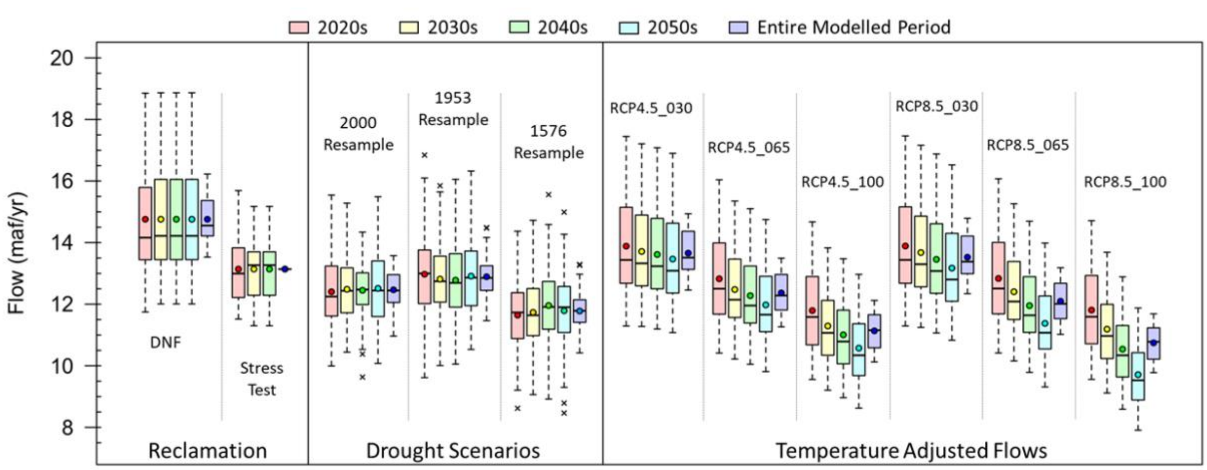

Figure 6.1. *Range and distribution of the sum of 20 naturalized Upper Basin inflows locations for the scenarios analyzed in this report.*

The *DNF* scenario uses the full period from 1906 to 2018, and every other hydrologic scenario has an average annual flow less than the *DNF* scenario. The scenarios with the lowest Upper Basin inflows are the *1576 Resample* and the climate perturbed scenarios using assumptions of a 10% decrease in runoff per degree warming (*RCP8.5_100* and *RCP4.5_100)*. Throughout our analysis, we used these scenarios, along with the *2000 Resample* scenario, to understand the implications of alternative management paradigms under severe shortage conditions or continuation of the current drought situation. The *2000 Resample* scenario is particularly plausible, because it simply assumes the conditions that the basin has experienced during the last 20 years are representative of a new normal. We also consider the RCP4.5_065 hydrologic scenario to be highly probable since the conditions it displays for the current decade most closely matches the hydrologic conditions experienced over recent years.

Each of these hydrologic scenarios is applied in CRSS with a depletion scenario, and each depletion scenario is fraught with uncertainties associated with estimates of future consumptive uses and losses upstream from Lake Powell (described below in Section 7). We developed two additional hydrologic inflow scenarios that reduce these uncertainties by using recent actual historical inflows into Lake Powell instead of using the CRSS to model the movement of water through the Upper Basin. We refer to one of these inflow data sets as the *Stress Test Actual UB Inflows*, which is analogous to Reclamation's 'Stress Test' hydrology, using the historical period from 1988 to 2018. The ISM method was used on the actual measured inflows to Lake Powell during this recent period to generate 31 traces. The other hydrologic data set that we developed was the *2000 Resample Actual UB Inflows,* which uses the Resampled Millennium Drought (2000-2018) period along with the corresponding actual annual inflow year to Lake Powell to produce 100 traces using the method of Salehabadi et al. (2020). Analyses of AMPs using these two data sets assume that Upper Basin hydrology and depletions in the future will be the same as they have in the recent past, thereby eliminating assumptions about future growth in Upper Basin consumptive uses and losses.

Each inflow scenario is summarized in Table 6.1. Further comparative analyses of the average Upper Basin inflows from each hydrologic scenario, which require specifications of both supplies and demands, are presented in Section 7.

Hydrology Scenario	**Description**
DNF*	113 historical flow traces resampled from 1906-2018 using Index Sequential Method
Stress Test*	31 historical flow traces resampled from 1988-2018 using Index Sequential Method
1576 Resample**	100 traces with years randomly resampled from Paleo Tree Ring Drought period of 1576-1600
1953 Resample**	100 traces with years randomly resampled from mid 20th Century Drought period of 1953-1977
2000 Resample**	100 traces with years randomly resampled from Millennium Drought period of 2000-2018

RCP 4.5_030***	112 traces resampled from 1906-2017 using Index Sequential Method with a 3% decrease in runoff for each degree of warming using RCP4.5 climate projections
RCP 4.5_065***	112 traces resampled from 1906-2017 using Index Sequential Method with a 6.5% decrease in runoff for each degree of warming using RCP4.5 climate projections
RCP 4.5_100***	112 traces resampled from 1906-2017 using Index Sequential Method with a 10% decrease in runoff for each degree of warming using RCP4.5 climate projections
RCP 8.5_030***	112 traces resampled from 1906-2017 using Index Sequential Method with a 3% decrease in runoff for each degree of warming using RCP8.5 climate projections
RCP 8.5_065***	112 traces resampled from 1906-2017 using Index Sequential Method with a 6.5% decrease in runoff for each degree of warming using RCP8.5 climate projections
RCP 8.5_100***	112 traces resampled from 1906-2017 using Index Sequential Method with a 10% decrease in runoff for each degree of warming using RCP8.5 climate projections
Stress Test Actual UB Inflows*	31 historical flow traces using actual inflows to Lake Powell resampled from 1988-2018 using Index Sequential Method
2000 Resample_Actual Inflow**	100 traces using actual inflows to Lake Powell with years randomly resampled from Millennium Drought period of 1953-1977

* Reclamation

** Salehabadi et al., 2020

*** Udall, 2020

Table 6.1. Description of Hydrologic Inflow Scenarios. See Table 7.1 for volumetric inflows by decade in the 21st century.

7. Future Upper Basin Depletions and Downstream Implications

Future consumptive water uses are inherently difficult to predict due to uncertainties regarding population growth, economic conditions, irrigation efficiency, and a growing societal recognition of the need to reduce per capita use of water. Furthermore, planning efforts to manage the Colorado River for future uses are complicated by stakeholders competing amongst each other to secure water allocations. This issue has become increasingly relevant as basinwide water scarcity has become more apparent. As shown previously in Figure 2.3, **Upper Basin uses and losses have been stable or slightly decreasing since 1988, and actual water uses in the Upper Basin have never been as large as the projected needs** (Wang et al., 2020).

The story of projections of future consumptive uses in the Upper Colorado River Basin has always been one of lofty aspirations of future development that eschewed the constraints imposed by the reality of the basin’s climate and topography. This conflict between aspirations and constraints was apparent in the first meetings of the Colorado River Compact Commission in January 1922, when the four headwater states (now referred to as the States of the Upper Division or Upper Division states) submitted estimates for future irrigation uses that were twice what the federal government considered technically and economically feasible (Kuhn and Fleck, 2019), and the overstatement of future uses has been a consistent theme of water planning ever since.

The original rationale to overestimate the projections of future Upper Basin use was attributable to the politics of developing water, to the concept of 'equity' between the Upper and Lower Basin, and the interest to protect legal entitlements negotiated in the 1922 Compact and other agreements that comprise the Law of the River. The Lower Basin developed many of its consumptive uses decades before the major developments in the Upper Basin, and negotiations sought to balance projected future uses in the Upper Basin with rapidly growing Lower Basin needs. State water agencies in the Upper Basin sometimes believed that high estimates of future depletions could help safeguard the potential for future Upper Basin water development. **However, overestimation of future consumptive uses in the Upper Basin unavoidably affects estimation of the amount of water that is available for Lower Basin consumptive uses, future tribal uses, future hydroelectricity generation, and future in-stream environmental uses.** Because most climate forecasts project declining watershed runoff, incorporation of exaggerated projections of future Upper Basin water use exacerbates the appearance of a disparity between future demand and supply.

7.1. Modeling the Future of the Upper Basin in CRSS

We used the 2007 Upper Basin projection of future consumptive uses (hereafter, 'depletion schedules') prepared by the Upper Colorado River Commission and incorporated into the CRSS by Reclamation (UCRC, 2007) (Figure 7.1). The projection embedded in CRSS estimates 5.10 maf/year of depletion requests in 2021 that increases to 5.57 maf/year in 2060. Reservoir evaporation is an additional consumptive loss which is a function of pool elevation and assumed monthly evaporation rates, and is dynamically simulated in the CRSS. The CRSS has not been updated to reflect the more recent 2016 UCRC future depletion schedules (UCRC, 2016), which also overestimates depletions as shown earlier in Figure 2.3.

The results from the CRSS model runs, which reflect current management and allocation agreements, further demonstrates how the 2007 UCRC future depletion schedule cannot be met. The average modeled consumptive uses by the Upper Basin States are consistently less than the 2007 UCRC future depletion schedule, even when assuming the *DNF* hydrologic scenario that is based on the hydrologic history that occurred between 1906 and 2018 (Figure 7.2). There is a 0.21 to 0.27 maf/year shortage when the CRSS model attempts to consume water according to the 2007 UCRC future depletion schedules. Not surprisingly, Upper Basin consumptive uses are even less when watershed runoff is that which is estimated for the three drought scenarios. Annual shortages of 0.48, 0.55, and 0.69 maf/year are estimated by 2060 when using the *1953 Resample*, *2000 Resample*, and *1576 Resample* hydrologic scenarios, respectively.

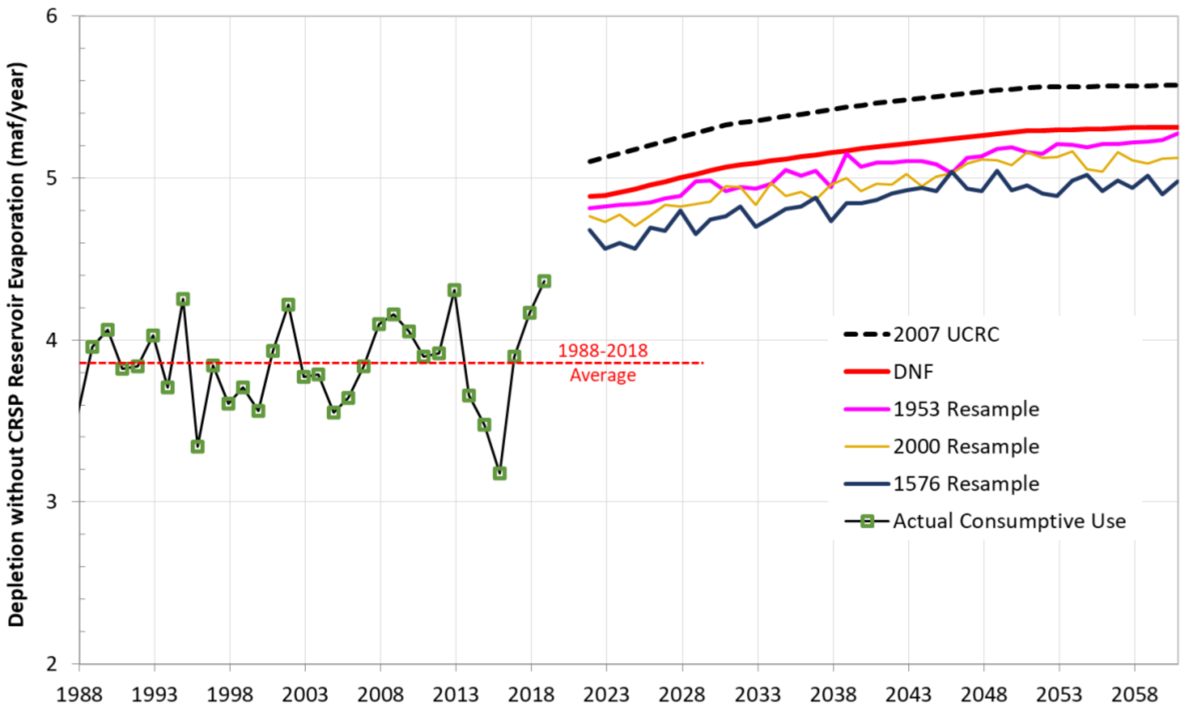

Figure 7.1. The 2007 UCRC future depletion schedule (black dashed line) and predicted total Upper Basin depletions which are unconstrained by compact requirements using the current configuration of the CRSS model with different hydrologic scenarios. Historical Upper Basin consumptive uses since 1988 are also shown (green squares). The red dashed line shows the stable average Upper Basin Use from 1988 to 2018. The difference between the black dashed line and any of the color lines reflects 'shortages,' in the sense that UCRC future depletion schedules are not achieved. Not even Reclamation's DNF hydrologic scenario based on 1906 to 2018 conditions can be fully satisfied.

Figures 2.3 and 7.1 demonstrate that planning for the future of the Colorado River should recognize the large uncertainty in estimating future depletions and the political nature of these projections. If Upper Basin consumptive uses are not as large as projected, then more water may be available for addressing downstream water supply and environmental needs, including environmental restoration opportunities in the delta and Salton Sea.

To reflect the well-established historical trend shown above, we also reconfigured CRSS to assume that there will be no future increases in consumptive water uses in the Upper Basin. We investigated this scenario (termed *UB Actual*) by assuming that recent historical inflows to Lake Powell will be representative of future inflows, thereby implying that recent watershed runoff and Upper Basin consumptive uses will persist. When modeling these scenarios, we allowed for additional releases from Flaming Gorge to be added to the inflows to Lake Powell according to the agreements of the Upper Basin DCP. We compared these scenarios with those that anticipate growth according to the 2007 UCRC future depletion schedule. This comparison allowed us to analyze the effects of increased Upper Basin consumptive water use on the Colorado River's hydrology and on future reservoir operations. This analysis is particularly relevant when assessing the risk of future shortage conditions resulting from droughts or from the expected flow declines caused by climate change.

Depleted inflows into Lake Powell are compared in Table 7.1 across all hydrologic scenarios and applying the two assumptions of Upper Basin depletions (i.e. the 2007 UCRC future depletion schedules and actual historical Powell inflows). The most extreme drought condition considered is the *1576 Resample* hydrologic scenario, resulting in one of the lowest predicted inflows to Lake Powell. The average predicted inflows across the 2021-2060 modeled period is estimated to be 6.94 maf/year. Hydrologic scenarios that represent ongoing temperature increases from climate changes and that assume a 10% decrease in runoff per degree warming (*RCP8.5_100* and *RCP4.5_100)* are predicted to result in average inflows to Lake Powell of 5.13 maf/year and 6.56 maf/year by the 2050s, respectively (Table 7.1). Each of these extreme conditions assumes Upper Basin consumptive uses increase according to the UCRC 2007 projections

Not surprisingly, we predict that inflow to Lake Powell will be greater if Upper Basin consumptive uses are less. The scenarios that assume no increase in Upper Basin consumptive uses (i.e. *Stress Test_UB Actual* and *2000 Resample_UB Actual*) predict inflows to Powell of 9.24 and 8.56 maf/year, respectively, across the modeled run period. Both scenarios demonstrate the amount of water savings that is possible from using more realistic future Upper Basin depletions.

	Sample Period	Avg Inflows into Lake Powell Avg Naturalized Hydrologic Inflows to Upper Basin (maf/year)				
		2020s	2030s	2040s	2050s	All
DNF*	1906-2018	9.71 14.76	9.56 14.76	9.42 14.76	9.35 14.76	9.50 14.76
Stress Test*	1988-2018	8.35 13.14	8.12 13.14	7.97 13.14	-- --	8.12 13.14
1576 Resample*	1576-1600	7.19 11.64	6.92 11.73	6.96 11.96	6.78 11.79	6.94 11.78
1953 Resample*	1953-1977	8.15 12.97	7.81 12.81	7.62 12.78	7.64 12.91	7.81 12.89
2000 Resample*	2000-2018	7.77 12.40	7.54 12.48	7.38 12.45	7.35 12.51	7.50 12.47
RCP 4.5_030*	1906-2017	9.00 13.88	8.63 13.71	8.41 13.62	8.18 13.47	8.53 13.66
RCP 4.5_065*	1906-2017	8.14 12.82	7.53 12.48	7.23 12.28	6.87 11.98	7.41 12.37
RCP 4.5_100*	1906-2017	7.30 11.79	6.53 11.29	6.11 11.01	5.65 10.57	6.36 11.13
RCP 8.5_030*	1906-2017	9.03 13.89	8.64 13.68	8.31 13.46	7.98 13.17	8.46 13.53
RCP 8.5_065*	1906-2017	8.14 12.84	7.53 12.41	7.23 11.95	6.87 11.38	7.41 12.10

RCP 8.5_100*	1906-2017	7.37 11.81	6.57 11.19	5.83 10.54	5.13 9.71	6.16 10.74
Stress Test_ Actual UB Inflows^	1988-2018	9.25 --	9.24 --	9.22 --	-- --	9.24 --
2000 Resample_ Actual UB Inflow^	2000-2018	8.55 --	8.61 --	8.53 --	8.56 --	8.56 --

* Uses 2007 UCRC depletion Schedules

^ Uses Actual Historical Powell Inflows plus Flaming Gorge DCP releases

Table 7.1. Average Lake Powell Inflows (black) and sum of 20 naturalized Upper Basin inflow locations (red) for all hydrologic scenarios analyzed in this report.

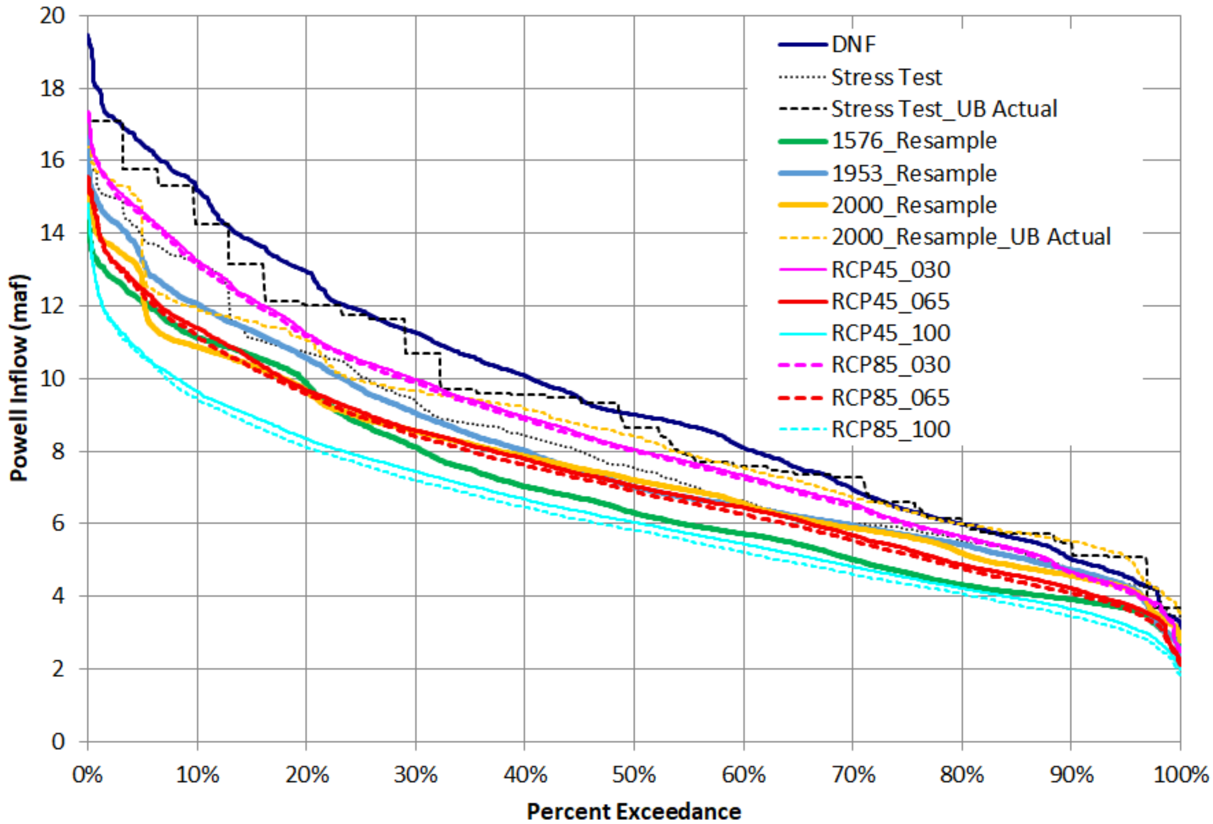

Figure 7.2. The range in predicted inflows to Lake Powell, represented as the percent of model runs that exceeded a specific value. The two model runs that assume no future increase in Upper Basin consumptive uses (i.e., UB Actual) have higher predicted inflows than do many of the model runs that assume progressive reduction in watershed runoff. Annual Lake Powell inflows and Upper Basin depletions were calculated by either the CRSS model subtracting the 2007 UCRC schedules from the naturalized Upper Basin inflows, or in the case of the UB_Actual scenarios, the actual historical inflows are used over the sample period associated

with each scenario (see Table 7.1). Modeled inflows are from 2021-2060 for all runs except the Stress Test and Stress Test_UB Actual which are from 2021-2051.

We evaluate the effect of Upper Basin consumptive uses by comparing the same hydrologic scenario under assumptions of no depletion growth and assumptions that consumptive uses progressively increase based on the 2007 UCRC future depletion schedule. We made this comparison for the *Stress Test* (1988-2018) hydrologic scenario and the *2000 Resample* hydrologic scenario (2000-2018). In the scenarios of no growth (*Stress Test_UB Actual* and *2000 Resample_UB Actual*), actual historical inflows are used as inputs to the CRSS model runs. Figure 7.3 shows predicted inflows to Lake Powell under the comparable hydrologic conditions, and we also show the predicted inflows assuming increasing Upper Basin uses with the most favorable hydrologic scenario—the *DNF* scenario**.**

Our results demonstrate the large impact of Upper Basin consumptive use on the ability to manage inflows to Lake Powell in a sustainable way. If Upper Basin hydrologic inflows remain at recent levels and consumptive uses continue to progressively increase, inflows to Lake Powell are predicted to progressively decrease, as evidenced by the decreasing trends in Figure 7.3 for the *Stress Test* and *2000 Resample* scenarios. In contrast, if consumptive uses do not increase, Lake Powell inflows would maintain a stable pattern that reflect the watershed runoff conditions of each hydrologic scenario. During the modeled period, the average inflow for the *Stress Test_UB Actual* and *2000 Resample_UB Actual* (dashed lines) is more than 1 maf/year more than the comparable *Stress Test* and *2000 Resample* scenarios (solid lines) that assume progressive growth in consumptive uses.

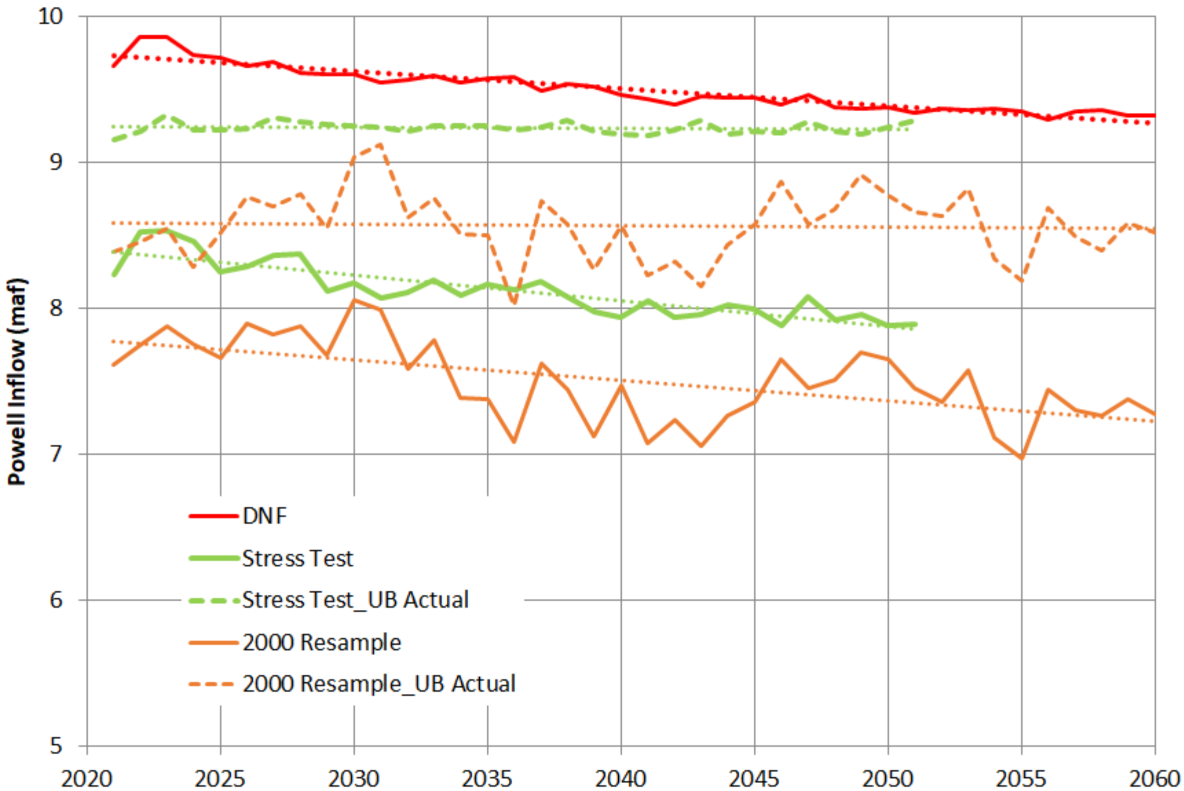

Figure 7.3. Inflows to Lake Powell using the Direct Natural Flow (1906-2018), Stress Test (1988-2018) and 2000 Resample (2000-2018) hydrologic scenarios, and comparing depletion scenarios of no growth in consumptive uses (UB_Actual; dashed lines) with the increases in Upper Basin consumptive uses according to the 2007 UCRC depletion schedule (solid lines). Dotted lines indicate trends.

For the Upper Basin to meet its downstream obligations under a likely interpretation of the 1922 Compact, inflow to Lake Powell must average at least 8.5 – 9.0 maf/year. This amount is needed to deliver 8.23 maf/year to the Lower Basin and Mexico, plus 0.3 to 0.7 maf/year needed to offset gross evaporation on Lake Powell (Wang and Schmidt, 2020). Our results are significant, because we demonstrate that the consumptive uses of the Upper Basin that occurred between 2000 and 2018 are, on average, sustainable even during the extremely dry conditions of the current Millenium Drought. However, if Upper Basin consumptive uses continue to increase as projected by the 2007 UCRC future depletion schedule, then the flow obligations at Lee Ferry cannot be achieved or an equivalent amount of Upper Basin consumptive uses would have to be curtailed during a continued drought.

Increase of consumptive water use in the Upper Basin has the potential to be a more important determinant of the sustainable management of the Colorado River's reservoirs than does the effect of decreasing runoff. We used the CRSS model to assess the implications of these hydrologic inflow scenarios on the storage of the Colorado River system. The combined end-of-year storage of Lake Mead and Lake Powell can be maintained at current levels if hydrologic conditions similar to the *Stress Test* period (1988-2018) occur into the future and if Upper Basin consumptive uses do not increase (i.e. *Stress Test_UB Actual* in Figure 7.4). However, if Upper Basin consumptive uses increase according to the 2007 UCRC future depletion schedule, then the *Stress Test* conditions will result in a continuous decline of reservoir storage. More serious drought conditions would further deplete the Colorado River reservoir system, even with the current consumptive uses. A continuation of the current drought (i.e. *2000 Resample*) and increasing Upper Basin depletions would cause a progressive decline of the reservoir storage until the total storage drops to about 5 maf, a level at which storage is dictated by the hydraulic head of the fully open outlet tubes. As a practical matter, there is no usable regulatory water available in Lakes Mead and Powell when total storage drops to about 5 maf. Even if Upper Basin depletions did not increase (*2000 Resample_UB Actual*), the total storage would fall to around 15 maf until sufficient Lower Basin shortages would allow the reservoirs to stabilize.

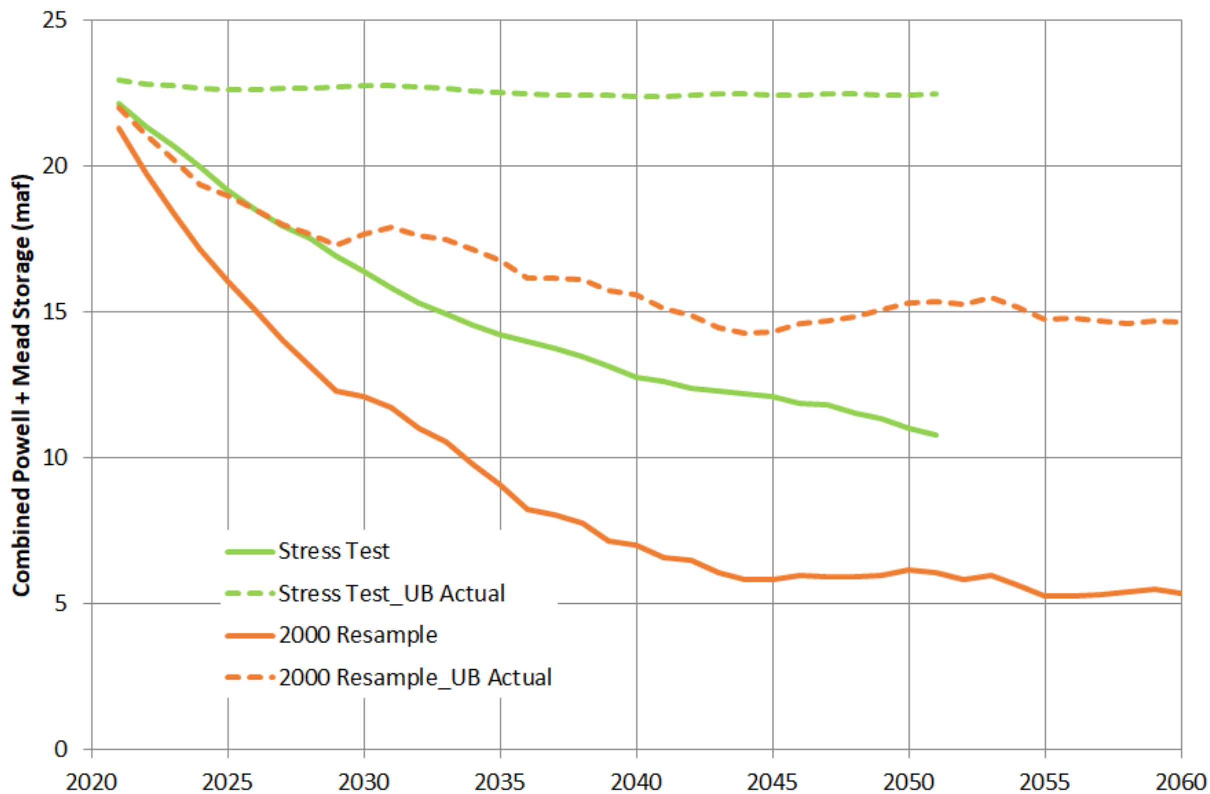

Figure 7.4. End-of-year combined Lake Powell and Lake Mead reservoir storage under the Stress Test (1988-2018) and 2000 Resample (2000-2018) hydrologic conditions, and considering the implications of the 2007 UCRC schedules (solid lines) and no increases in depletions (dashed lines).

Maintaining current Upper Basin consumptive uses would significantly lower the risk of shortages to the Lower Basin and Mexico under plausible future drought conditions (Figure 7.5).

The *Stress Test* hydrologic scenario and the *2000 Resample* hydrologic scenario would result in sharp increases in shortages if the 2007 UCRC future depletion schedule is realized. However, no additional significant impacts would occur (beyond what would be predicted to occur assuming Reclamation's 1906-2018 DNF hydrology) if Upper Basin depletions remained similar to the 1988-2018 period (*Stress Test_UB Actual*). If the drought that has occurred since 2000 became a 'new normal' condition and the Upper Basin did not develop additional water, average shortages to the Lower Basin and Mexico would remain around 1 maf (*2000_Resampled*). Both of these scenarios, however, do not include the substantial likelihood of a compact deficit leading to the possibility of curtailments in the Upper Basin under Article IV of the 1948 Compact and possible extended interstate litigation.

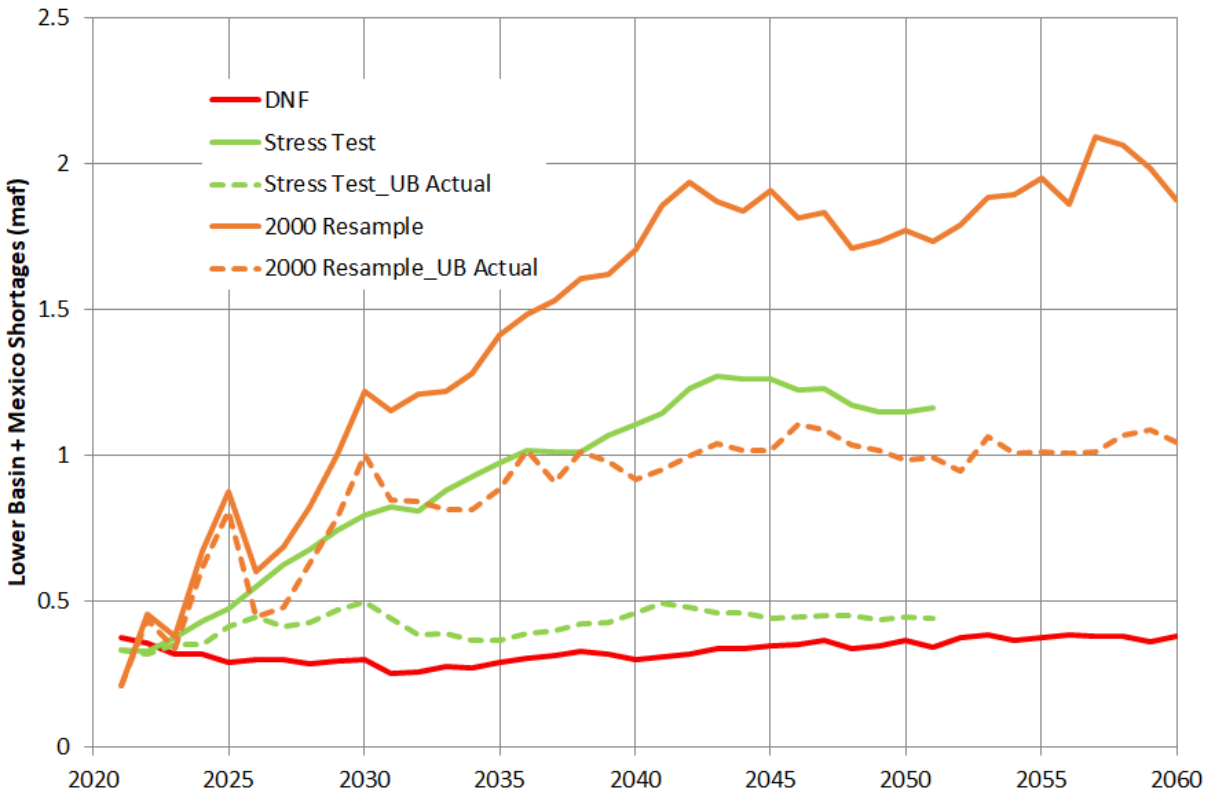

Figure 7.5. Total Lower Basin shortages including Mexico using the Stress Test (1988-2018) and 2000 Resample (2000-2018) hydrologic scenarios, and comparing future depletion scenarios of no growth in consumptive uses (UB_Actual; solid lines) with the increases in Upper Basin consumptive uses according to the 2007 UCRC schedule (dashed lines).

7.2. Implications of Upper Basin depletions on Compact Compliance

The States of the Lower Division have consistently taken the position that the Upper Basin's total 1922 Compact obligation is 82.5 maf per 10 years, and perhaps slightly more if transit losses are considered. The States of the Upper Basin have historically taken the position that their delivery obligation to the treaty with Mexico has never been quantified, therefore, their total compact obligation could be as low as 75 maf per 10 years. Thus, on the high side, the Upper Division states would be in violation of the 1922 Compact if 10-year cumulative flows passing Lee Ferry drop below 82.5 maf. On the low side, the compact curtailment would not have to occur until 10-year cumulative flows drop below 75 maf. To make up a deficit, the Upper Division states may have to implement a compact curtailment (sometimes referred to as a 'compact call') under Article IV of the 1948 Compact. Disputes over a formal curtailment could easily result in extended interstate litigation. **Reclamation's standard application of CRSS with the *DNF* Hydrology (1906-2018) and the 2007 UCRC future depletion schedule predicts that there is a relatively low probability that 10-year cumulative flows passing Lee Ferry will be less than 82.5 maf and zero probability of less than 75 maf** (Figure 7.6). This analysis shows why both basins are falsely comforted by the use of the full DNF hydrologic record for planning purposes. The average natural flow at Lee Ferry for the 1906-2018 period of 14.8 maf/year is an amount that climate science concludes is unlikely to occur in the future.

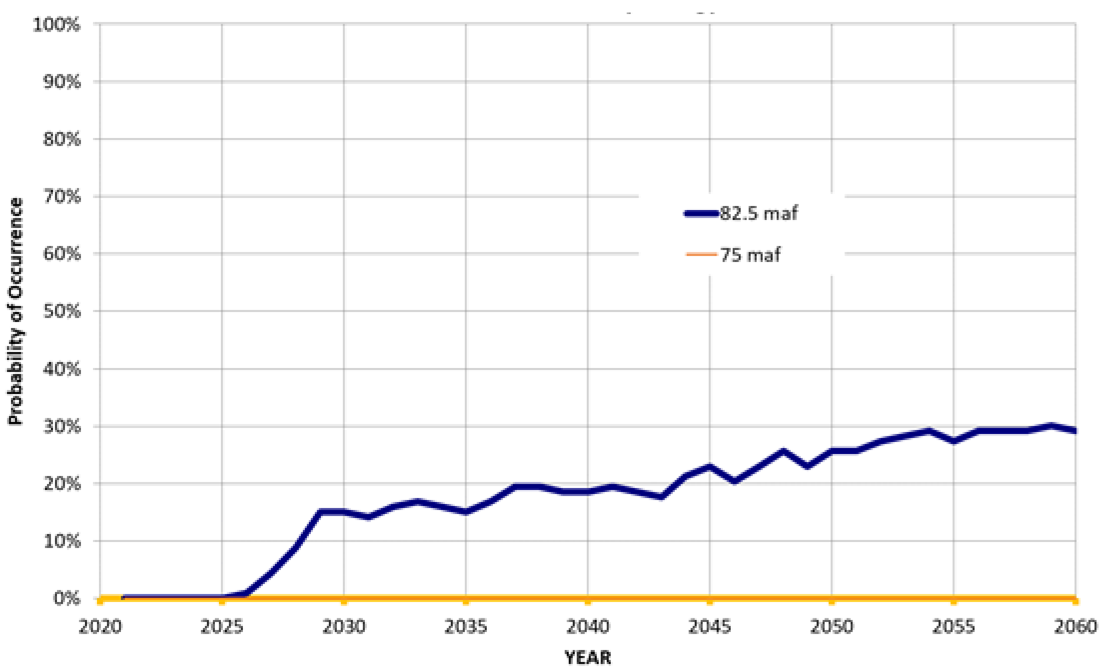

Figure 7.6. The probability of 10-year cumulative flows at Lee Ferry falling below the perceived compact release requirements of 75 maf and 82.5 maf when using the Direct Natural Flow hydrology and assuming the 2007 UCRC future depletion schedule.

The situation is substantially different when considering sustained periods of future low runoff conditions as climate science predicts. If future consumptive uses of water in the Upper Basin continue to increase as suggested by the 2007 UCRC future depletion schedule, and that future hydrology is represented by the *2000 Resample*, *1953 Resample*, and *1576 Resample* scenarios, the median value of all 100 traces for each of the three scenarios suggests it is likely that flows at Lee Ferry would fall below the 10-year cumulative threshold of 82.5 maf within eleven years (Figure 7.7). A continuation of the current drought that has occurred since 2000, or the onset of a drought equivalent to the magnitude of that which began in 1576, would likely result in a 10-year cumulative delivery to the Lower Basin of less than 75 maf after 23 and 15 years, respectively. However, if the current drought persists, but the Upper Basin consumptive uses do not increase (2000 Resample_UB Actual), there is a high likelihood of continued 10-year cumulative delivery of 82.5 maf at Lee Ferry, thus avoiding the risk of a 'compact call.' This is a very significant finding for the Upper Division states.

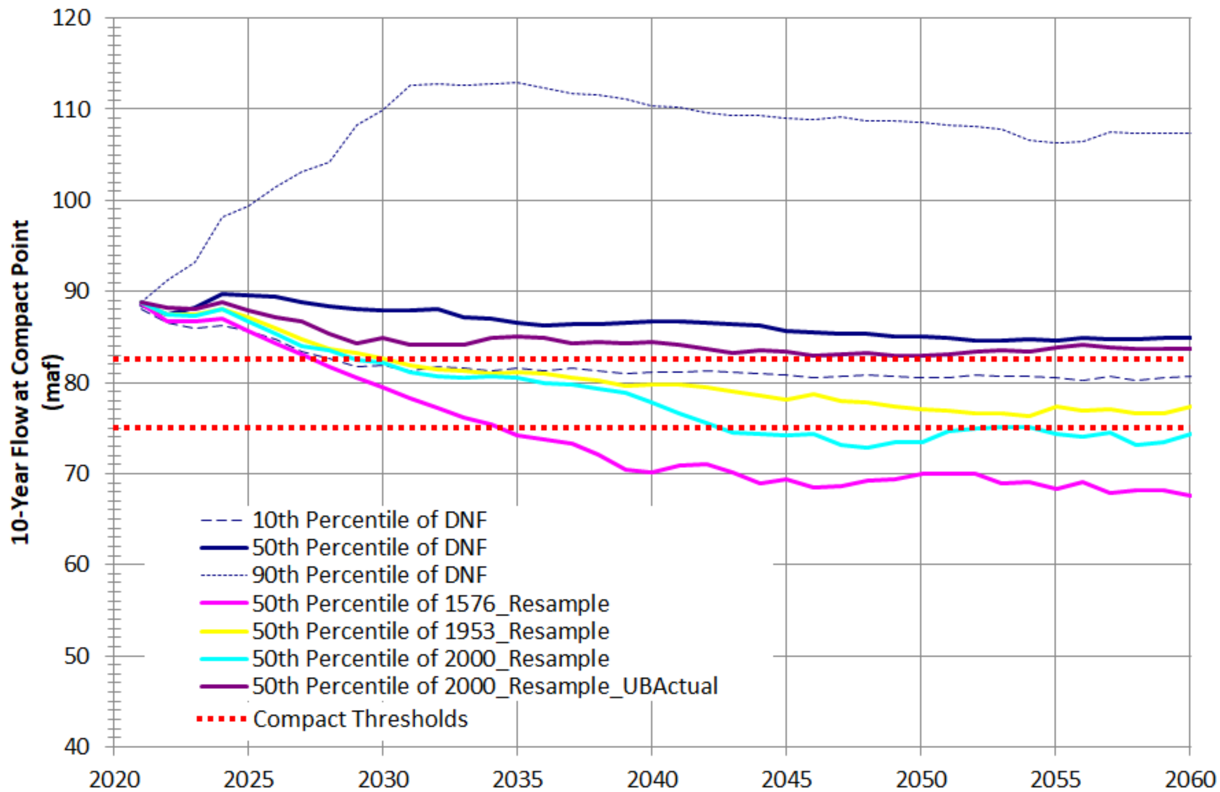

Figure 7.7. Cumulative 10-year flows at Lee Ferry using the *DNF*, *1576 Resample*, *1953 Resample* and *2000 Resample* hydrology scenarios. In addition, the 2000 Resample hydrology is shown without increases to Upper Basin depletions (*2000 Resample_UBActual*). The 10th, 50th, and 90th percentiles for the DNF are shown, and the 50th percentile (most likely) is shown for the four drought scenarios. Horizontal red lines indicate the 75 maf and 82.5 maf compact thresholds. The 50th percentile lines for the three drought scenarios indicates that these conditions are likely to cause Compact deficits if Upper Basin demands increase, but the *2000 Resample_UBActual* shows that Compact deficits from a continuation of the current drought can most likely be avoided if Upper Basin depletions remain unchanged.

7.3. Upper Basin Voluntary Demand Caps

In addition to our analysis of the effect of the aspirational increases in Upper Basin consumptive water use reflected in the 2007 UCRC future depletion schedule, we also used CRSS to examine the implications of managing Upper Basin depletions through a limit on the total annual depletions allowed (Colorado River Governance Initiative, 2013).[1] This approach is sometimes referred to as the 'Upper Basin Cap.' By conducting a sensitivity analysis using a range of 'Demand Caps' between 3.0 maf/yr and 5.0 maf/yr, we examined the operation of the Colorado River system during drought or under the assumption that climate change reduces natural flows at Lee Ferry to levels similar to the *Resample 2000 (avg natural inflow = 12.47 maf)*, *1953 Resample (avg natural inflow = 12.89 maf)* and *1576 Resample (avg natural inflow = 11.78 maf)* scenarios.

Average projected Upper Basin depletions assuming three different hydrologic conditions (*DNF*, *Resample 2000* and *Resample 1576*) are shown in Figure 7.8, 7.9 and 7.10, respectively. The actual average 1988-2018 consumptive use is shown for reference. Each figure shows three different assumptions about Compact compliance (no compliance, 75 maf and 82.5 maf deliveries) and six different Upper Basin demands (3.0, 3.5, 4.0, 4.5, 5.0 maf Demand Caps and No Cap). The No Cap demand is an attempt to meet the aspirational UCRC 2007 future depletion schedule, which is also shown at the top of each figure. Solid lines show how much water would be available for the Upper Division states if they had no Compact obligations at Lee Ferry. The dashed (75 maf Compact compliance) and dotted lines (82.5 maf Compact compliance) indicate the average depletions with Compact compliance in place. Note that in many cases, especially with lower depletion levels, all three lines sit on top of each other.

Figure 7.8 considers only Reclamation's *DNF* hydrology (1906-2018). As shown earlier, the CRSS results indicate that the 2007 UCRC future depletions schedule cannot be met and a shortage of at least 0.21 maf/year would occur throughout the analysis period due to physical limitations in the Upper Basin. Despite these relatively wet hydrologic assumptions and the median probability of the 10-year flows staying slightly above 82.5 maf (Figure 7.7), the Upper Division states still face a risk of under this compact threshold if demands are equal to or above 4.0 maf/year (dots). The average curtailment magnitude is generally small in size, especially if compared to curtailments expected during drought conditions shown in Figures 7.9 and 7.10.

[1] To conduct this sensitivity analysis, it was necessary to utilize a function in the CRSS model that quantifies the amount of Compact deficits by determining the running quantity of shortfalls to a predefined threshold of deliveries from the Upper Basin to the Lower Basin (i.e., either 75 maf or 82.5 maf/10 years) and then simulates the implication of curtailments to the Upper Division states. Such an approach requires 'injecting' water into the system upstream from Lake Powell that is equivalent to this shortfall and letting the water pass through Lake Powell in the same month that it is introduced. Concurrently, when reporting depletions in the Upper Basin, the annual volume of this shortfall was deducted from the modeled volume of annual depletions in the Upper Division. This method to account for Compact deficits was originally used by Reclamation in the Basin Study; however that analysis only used a 10-year cumulative threshold value of 75 maf and did not consider a threshold of 82.5 maf, which the Lower Basin prefers.

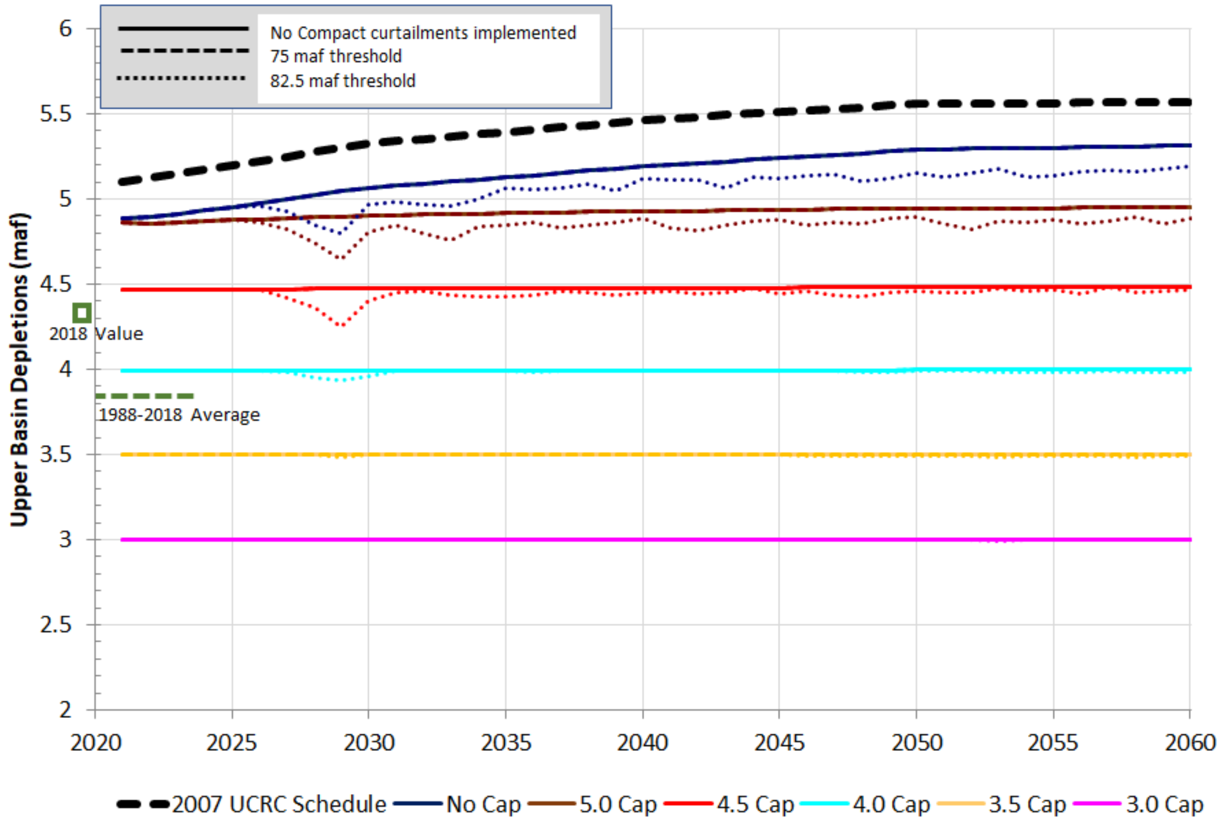

Figure 7.8. Average Upper Basin depletions that consider Compact curtailments using 75 maf and 82.5 maf 10-year compact thresholds, along with various capped Upper Basin depletion levels and assuming a *DNF* hydrology (1906-2018). Solid lines indicate no Compact curtailments are applied. Dashed and dotted lines assume the 75 maf and 82.5 maf Compact thresholds respectively to apply Upper Basin curtailments.

When considering future hydrology with a continuation of the current drought (*2000 Resample*) or a return of the Paleo Tree Ring Drought (*1576 Resample*), Figures 7.9 and 7.10 show that the Upper Division states would face frequent and large compact deficits requiring curtailments regardless of which Compact threshold is used. The depletions in the Upper Division states could be curtailed as early as 2026 under the 82.5 maf Compact threshold if the current drought persists, or by 2025 if the drought worsens to be similar to the Paleo Tree Ring Drought. Under the 75 maf threshold, depletions in the Upper Division states could be curtailed as early as 2027 under the Paleo Tree Ring Drought, or by 2029 under a continuation of the current Millennium Drought. This analysis shows that crossing these Compact thresholds could occur much sooner than the dates suggested in Figure 7.7, which only considered the median values across 100 traces.

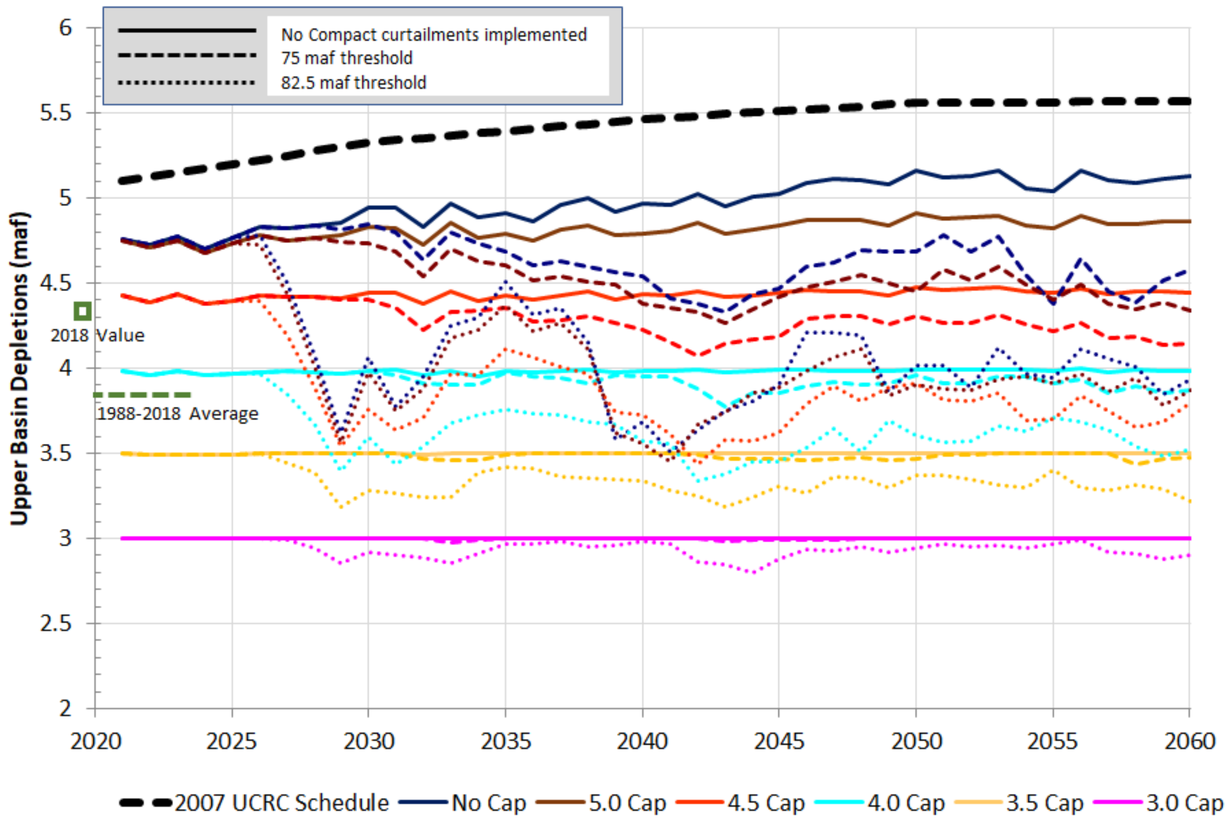

Figure 7.9. Average Upper Basin depletions that consider Compact curtailments using 75 maf and 82.5 maf 10-year compact thresholds, along with various capped Upper Basin depletion levels and assuming a continuation of the current Millennium Drought (*Resample 2000*). Solid lines indicate no Compact curtailments are applied. Dashed and dotted lines assume the 75 maf and 82.5 maf Compact thresholds respectively to apply Upper Basin curtailments.

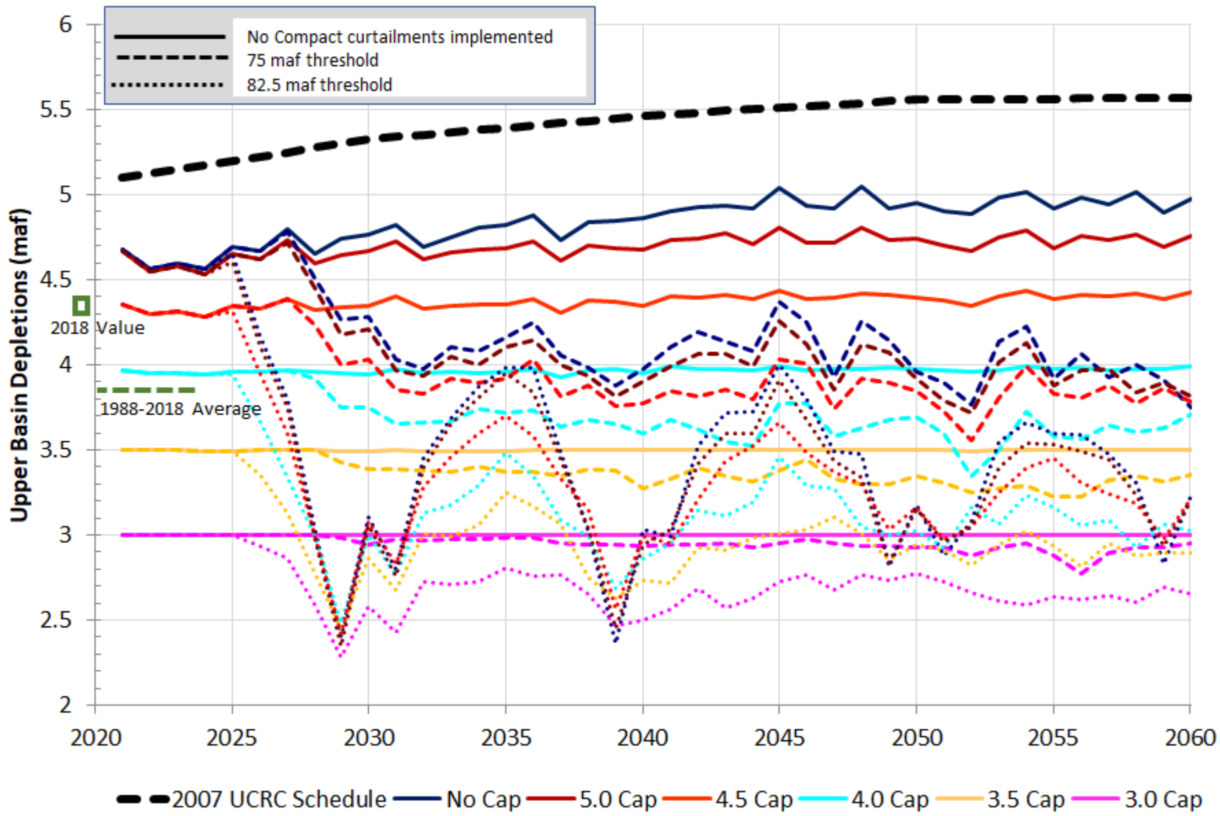

Figure 7.10. Average Upper Basin depletions that consider Compact curtailments using 75 maf and 82.5 maf 10-year compact thresholds, along with various capped Upper Basin depletion levels and assuming the onset of a continuation of the Paleo Tree Ring Drought (*Resample 1576*). Solid lines indicate no Compact curtailments are applied. Dashed and dotted lines assume the 75 maf and 82.5 maf Compact thresholds respectively to apply Upper Basin curtailments.

Figures 7.9 through 7.10 clearly show that existing consumptive uses in the Upper Division states are at significant risk due to the combination of fixed Compact obligations at Lee Ferry (the 10 year cumulative 82.5 or 75 maf thresholds) and the risk of recurring drought or equivalent implications of climate changes. It is important to remember that over the period of 1988-2019 annual Upper Basin consumptive uses averaged about 3.86 maf without evaporation, and the most recent estimation in 2018 was 4.37 maf. Figure 7.9 assumes a continuation of the Millennium Drought (*Resampled 2000***)**, and even if there were no Compact constraints, CRSS limits water availability such that total annual Upper Basin depletions are about 0.55 maf/year less than the UCRC 2007 future depletion schedule. If Compact curtailments do occur with the 75 maf threshold, annual Upper Basin depletions vary between about 4.4 and 4.8 maf/year, only slightly more than recent levels. Using the 82.5 maf threshold, curtailments beginning in 2028 drop Upper Basin depletions to a range of 3.5 - 4.4 maf/year, well below the 1988-2018 average uses.

Under the assumption that future flows fall to levels seen during the Paleo Tree Ring Drought (*Resampled 1576*), the impacts to existing uses in the Upper Basin are even more significant (Figure 7.10). Under the 82.5 maf threshold, the curtailments necessary to cover Compact deficits drop total annual uses to less than 2.5 maf/year—a level approaching the depletion level representing the use of only pre-Compact rights in the Upper Division states.

Assuming the UCRC 2007 schedule, the Upper Division states would face repeated curtailments with runoff similar to the Paleo Tree Ring Drought. During any above average years of runoff, the aspirationally high depletion schedule drives up Upper Basin withdrawals, creating bigger deficits later in the 10 year period. The result is a 10-year periodicity (as evidenced by the 'dips' in Figures 7.9 and 7.10) of increased risk of curtailments. Under scenarios where depletions did not increase (i.e. *UB Actual* scenarios), water from these above average years would be stored in Powell and used to avoid curtailments. The analysis of the different cap levels shown in Figures 7.8 through 7.10 are useful to both evaluate the Upper Basin's reliable yield available to the Upper Division states under future hydrologic scenarios, and to evaluate potential comprehensive solutions between the two basins.

The concept of a *Grand Bargain* is one such comprehensive solution that has been recently discussed, where in return for an Upper Basin development cap, the Lower Basin would not enforce the Upper Basin's delivery obligations at Lee Ferry (no compact curtailments). This was first proposed by Upper Division state representatives in 2005 (Kuhn, 2012). Figures 7.9 and 7.10 show that there is a clear advantage to the Upper Division states to again consider such an arrangement, especially given that climate science is pointing toward a continuing decline in future flows at Lee Ferry. The basic trade off is that the Upper Division states are limiting their future consumptive uses in return for certainty of a fixed amount of existing uses. If future flows continue to decline, they are better off. If future flows do not decline and return to pre-millennium drought levels, they have given up water. The potential advantage to the Lower Division states is not as clear, however it does avoid the risk of extended litigation that would occur during a time of potential crisis. If the Upper Basin Cap is set sufficiently low or if future flows return to higher levels, the Lower Basin States would gain water in this formulation of a *Grand Bargain*.

The analysis of the caps is also useful for evaluating *non-Grand Bargain* solutions such as the implementation of a large-scale demand management program in the Upper Division states. Figure 7.9 shows that under the assumption that future flows will be similar to the Millennium Drought levels and the Compact threshold is 82.5 maf, using demand management to protect a 4 maf/year level of depletion will require an additional periodic reduction of consumptive uses of about 0.3 to 0.6 maf/year, which is the difference between the solid light blue and dotted light blue lines. Figure 7.10 shows that if future flow levels drop to the Paleo Tree Ring Drought levels, maintaining that same 4 maf/year level would require an additional 1.0 maf/year of demand management cutbacks and up to 1.5 maf in some years. Under the assumption that future flows remain at the Millennium Drought levels or drop to Paleo Tree Ring Drought levels, the use of demand management to maintain the current level of existing uses, about 4 maf/year, will require the implementation of a very large demand management program. Whether such a program would be technically, economically, and politically feasible is questionable.

8. Comparing Outcomes of Alternative Management Paradigms

We chose several metrics related to both water-supply and ecosystem responses to compare the outcomes of several Alternative Management Paradigms (AMPs; Section 4) combined with various scenarios of future climate conditions and depletions (described in sections 6 and 7). Our goal was to explore how the various management alternatives influence both water security and important ecosystem drivers in a warming world in which watershed runoff declines, as well as under conditions of prolonged drought. In this section, we define the metrics related to water supply, hydropower, and ecosystem drivers. We also describe their importance, and how they will be used to compare AMPs. Additional metrics that evaluate ecosystem conditions are presented in forthcoming work as part of this White Paper Series (see Schmidt, Bruckerhoff et al., in prep).

8.1 Water Supply and Hydropower Metrics

The original purpose of developing infrastructure on the Colorado River was to allow agricultural lands to expand by assuring that a sufficient and reliable water supply would be available to meet current and expected irrigation needs. Infrastructure was also needed to minimize the risks of flooding that had proven to be devastating to farming, particularly in California along the lower river. With the construction of Hoover Dam, these objectives began to be realized, alongside large-scale hydropower generation. As future projects were developed in the Upper and Lower Basins, water use and hydropower generation expanded in an attempt to meet the growing demands for agricultural production and water supplies and power for rapid urbanization. However, the ability of the system to meet those needs remains in question. Here, we provide a variety of water supply and hydropower metrics that are immediately used in this study (described below), as well as identify a number of metrics that can be considered in future analyses (see Appendix 1).

Lower Basin Water Supply

As described in Section 2, the 1964 Supreme Court decree of Arizona v. California defined annual allocations among the Lower Basin States of California, Arizona, and Nevada of 4.4 maf, 2.8 maf, and 0.3 maf, respectively. Furthermore, the 1944 Treaty between the United States and Mexico guaranteed 1.5 maf/year delivery to Mexico. Codified in the 2007 Interim Guidelines, the DCP, and the Minutes 319 and 323 of the international treaty, deliveries to these four major entities—California, Arizona, Nevada, and Mexico—are all granted additional water during times of 'surplus,' and reductions during times of 'shortage.' In this context, a 'shortage' refers to the difference between the volume of water that each entity is entitled to under normal water supply conditions and what they actually receive. These shortages can be the result of intentional reductions in requested releases that are a result of policies such as the DCP or Minute 323, or hydrologic shortages due to the lack of available water to meet the requested demands in and downstream of Lake Mead. Thus, a 'shortage' is not necessarily a crisis situation, but may actually be a well planned and executed reduction of annual use to manage declining storage levels in Lake Mead.

Consequently, a basic metric to evaluate the performance of any policies, including the alternative management paradigms presented in the paper, is the reliability of delivering the aforementioned apportionments to the three Lower Basin States and to Mexico. An aggregate metric is used that evaluates the total expected shortages to a 9.0 maf delivery for the Lower Basin users including Mexico (Table 8.1).

Political Entity	**Water Supply Metric**
California	Annual Shortage from 4.4 maf
Arizona	Annual Shortage from 2.8 maf
Nevada	Annual Shortage from 0.3 maf
Mexico	Annual Shortage from 1.5 maf
Total Lower Basin and Mexico	Annual Shortage from 9.0 maf

Table 8.1. Lower Basin Water Supply metrics

Upper Basin Water Supply

As described above, the Upper Basin has not yet utilized its allocation according to Article III(a) of the 1922 Compact. In addition, there is no certainty that future water supplies and compact obligations will ever allow the Upper Basin States to utilize the aspirational depletion schedules as presented by the UCRC. As described in Section 7, it is highly improbable that these future depletion schedules will actually occur. Furthermore, the 1948 Upper Basin Compact divides the water available to the Upper Basin among the five states with lands in the Upper Basin first by allocating 50,000 af to Arizona and the remainder by percentages among Colorado, New Mexico, Utah, and Wyoming. Finally, there are many complicated and unresolved issues related to the administration of a curtailment under the 1948 Compact. As a result of these complexities, the most reasonable metric for evaluating the needs of the Upper Basin is the cumulative amount of water depleted across all users in the Upper Basin.

Pool Elevation or Storage Volume of Reservoirs

Many stakeholders on the Colorado River have become accustomed to using the pool elevations of Lake Mead and Lake Powell as a standard metric of the state of the river system. This metric informs the immediate concerns of particular users of the reservoirs, such as the Bureau of Reclamation that manages the generation of hydropower based on the hydraulic head differences across a dam, the Western Area Power Administration that markets the power generated, and boaters who recreate on the reservoirs. Furthermore, pool elevations have a relevance to the temperature of water released from reservoirs which has a direct effect on downstream ecosystems, as discussed in more detail in the next section. Pool elevations also have a particularly strong institutional relevance for the current water management paradigm on the Colorado River. Declarations of surplus and shortage conditions for the Lower Basin States and Mexico are presently determined by the pool elevation thresholds of Lake Mead on particular dates. The annual release from Glen Canyon Dam is also decided by a combination of the pool elevations of Lake Mead and Lake Powell. This institutional norm of using pool elevations as metrics for determining water management decisions has been increasingly normalized since the 2000 Surplus Criteria.

The critical pool elevations are clearly defined on Lake Mead and Lake Powell with respect to power generation and boating, but less so with respect to water temperature and ecosystems. Table 8.2 shows some of the critical elevations of Lake Powell's Glen Canyon Dam and Lake Mead's Hoover Dam.

Dam Characteristic	**Glen Canyon Dam**	**Hoover Dam**
Crest Elevation	3715 ft msl	1232 ft msl
Protection Elevation	3525 ft msl	1000 ft msl
Top of Conservation Pool (i.e. Minimum Power Pool)	3490 ft msl	950 ft msl
Top of Penstocks	~3470 ft msl	~900 ft msl
Top of Dead Pool	3370 ft msl	895 ft msl
Streambed at Dam Axis	3132 ft msl	640 ft msl

Table 8.2. Key pool elevations for Lake Powell and Lake Mead metrics

Metrics relative to these pool elevations can be used to evaluate the impact of any scenario on the water security of the Colorado River. A typical metric includes the likelihood of Lake Powell falling below its Protection Elevation of 3525 ft msl (i.e. specified in the Upper Basin DCP at a 'Target Elevation' for drought protection operations to protect Lake Powell from falling to the minimum power pool of 3490 ft msl) or Lake Mead falling below 1000 ft msl (i.e. the standard protection level for the intake for Southern Nevada Water Authority). Other elevations are relevant with regard to the current operations, such as the declaration of shortages to the Lower Basin if the pool elevation of Lake Mead falls below tiers specified in the DCP ranging from 1090 ft msl to 1025 msl. However the relevance of these elevation changes if the policies that incorporate them change.

The pool elevations of the reservoirs can have ecological implications due to their effect on the temperature of water releases from the reservoirs, which is discussed below. Pool elevations may also have ecological impacts through their effects on both the relative amount of reservoir versus riverine habitat and impacts on fragmentation and connectivity. Lower reservoir levels lead to increased riverine habitats that could be beneficial to native fishes. However, lower reservoir levels also lead to the potential formation of barriers that can form when reservoir levels drop. For example, Pearce Ferry Rapid was recently exposed due to the falling elevation of Lake Mead below 1135 ft msl. The ecological impacts of this barrier are currently not well understood. If this rapid is a barrier to non-native fish, it might benefit native fish upstream by keeping non-native fish from Lake Mead out of western Grand Canyon. However, fragmentation due to barriers also impedes the movement of native fishes. Although the relative abundance of native fishes in western Grand Canyon has increased since the formation of Pearce Ferry rapid, this change in community structure coincided with increases in river temperatures and increases in riverine habitats due to lower Lake Mead levels (Kegerries et al., 2020). Current research seeks to determine the importance of Pearce Ferry rapid on native and non-native fishes.

From a water management perspective, the storage volume of a reservoir is typically more relevant than pool elevation, and the relationship between elevation and stored water is non-linear. Reservoir storage on over-year storage facilities provides a sensible metric of how much capacity the system has to buffer the effects of future droughts. Metrics of the individual storages of Lake Mead and Lake Powell are relevant, but due to the complex rules that govern the coordinated management of the two reservoirs, a preferred metric from a water supply and planning perspective is the combined storage of these two major reservoirs. The total system storage is rarely reported by Reclamation, potentially due to the institutional divisions that perceive Lake Powell as the part of the Upper Basin and Lake Mead as part of the Lower Basin, while in fact they both serve the same basic purpose of regulating water for the Lower Basin.

Presentation of reservoir elevations or storage volumes over multiple hydrologic traces have been provided in earlier sections of this paper. These can be as simple as a time-series plot with time on the X-axis and the average elevation or storage volumes across all traces on the Y-axis (see Figure 7.5 for an example) or percentiles across all traces on the Y-axis (see Figure 7.7 for an example). Alternatively, probability metrics across all elevations (or possible storage volumes) of a reservoir can also be represented in a single graph as exceedance probabilities indicating the proportion of all model runs and over the run period in which pool elevations (or storage volumes) were equaled or exceeded. Figure 8.1 demonstrates this output for pool elevations of Lake Powell during the next 40 years comparing multiple hydrologic scenarios.

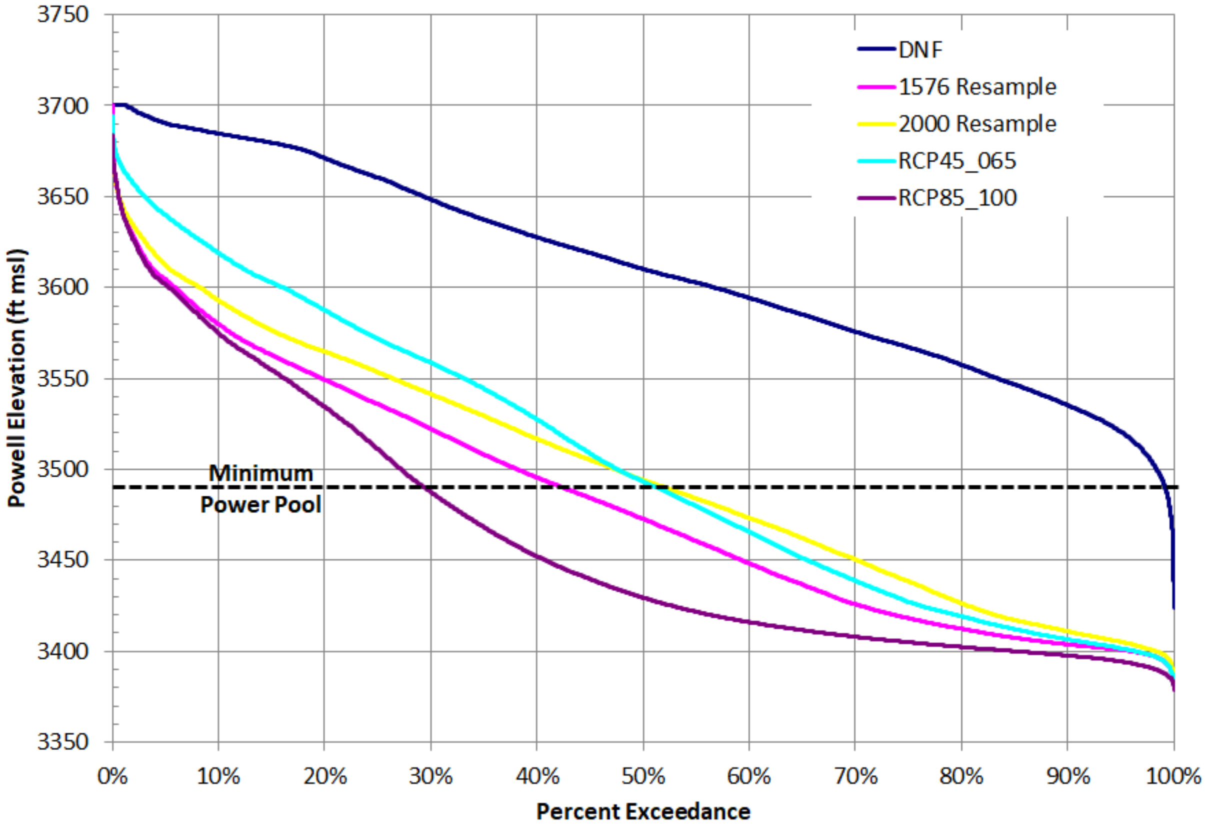

Figure 8.1. Percent exceedance of Powell Pool elevations using the *1576 Resample, 2000 Resample, RCP45_065* and *RCP85_100* hydrologic scenarios.

The intersections of the horizontal line with other lines shows the percentage of time that Lake Powell elevations would be greater than the minimum power pool. Thus, the blue line shows that 99% of the time across 113 model runs, Lake Powell pool elevations were predicted to be greater than the minimum power pool when considering the DNF scenario. However, if the 2000 Resample scenario is a more accurate depiction of the future watershed hydrology, then, in only 52% of the time across the 100 runs, would the storage level in Lake Powell be greater than the minimum necessary to generate electricity during the next 40 years. If each run is considered equally probable, then this type of plot presents probabilistic representation of the modeled results.

Another useful metric derived from reservoir elevations or storages is the duration of time that a reservoir might fall below a particular value, such as the key pool elevations shown in Table 8.2. As an example, the thick red line in Figure 8.2 shows the maximum duration that Lake Powell fell below each pool elevation using the *2000 Resample* hydrology scenario over 100 traces of the 40 year-model run. In at least one instance across all 100 model runs, the pool elevation fell below the minimum power pool of 3490 ft msl for 20 consecutive years. The thinner lines on this plot show the duration of time, represented as a percentile for all instances, when the pool elevation fell below each value—i.e. 95% of all instances when the pool elevation fell below 3490 ft msl lasted less than eight years, or 5% of instances lasted greater than eight years.

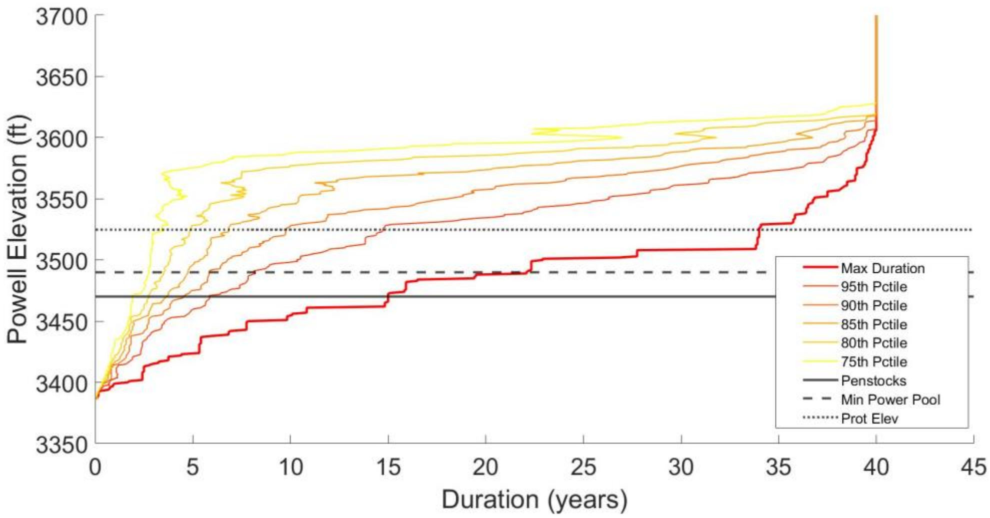

Figure 8.2. Maximum sustained duration of time below each Lake Powell elevation using the *2000 Resample* hydrology scenario, and percentiles for all instances that occur below these elevations.

System Losses

In the Colorado River system, reservoir evaporation is a significant loss of water supply. The total evaporative loss from Lake Mead and Lake Powell is approximately 1 maf/year when the two reservoirs are each half full. The loss is approximately 0.8 maf/year when each reservoir is approximately 30% full (Schmidt et al., 2016). In light of declining watershed runoff, it makes sense to implement water storage strategies that reduce evaporative loss, because the reduction in loss is the equivalent to an increase in supply.

Although reservoir evaporation is a physical process that is unavoidable, this loss is administratively accounted for in different ways in the Lower Basin and in the Upper Basin. Under the Arizona v. California decree accounting, reservoir evaporation losses are not charged against the consumptive uses of any of the Lower Basin States. Sustainable management of Lake Mead necessitates releases from Lake Powell plus intervening inflows sufficient to meet the consumptive needs of Arizona, California, Mexico, and Nevada, as well as the evaporative losses at Lakes Mead, Mohave, and Havasu. In contrast, under the 1948 Upper Basin Compact, 'net' evaporation from Lake Powell, Flaming Gorge, and the Aspinall Unit is considered a beneficial consumptive use and proportionally charged to each of the Upper Basin States. Thus, the total evaporation from these reservoirs reduces the amount of water available for consumptive use under the 1922 Compact.

The CRSS model reflects the differing approaches for considering evaporation losses in the Upper and Lower Basin with each using different calculation procedures for Lakes Mead and Powell. Evaporative losses at Lake Mead are determined as the total volume of water that is estimated to have evaporated based on dynamically changing surface areas and fixed monthly evaporation rates. The evaporative losses at Lake Powell are calculated using an administrative procedure called ‘net evaporation’ that seeks to avoid charging the Upper Basin States for evaporation that would occur had humans not impacted the hydrology landscape. Calculation of the net evaporation volume begins with the estimated total or ‘gross’ reservoir evaporation determined using the dynamically changing surface area of the reservoir and fixed monthly ‘gross’ evaporation rates, which is then reduced by the ‘salvage’ evaporation volume that represents the estimated evapotranspiration that occurred along the Colorado River in Glen Canyon before Glen Canyon Dam was constructed. This ‘salvage’ evaporation volume is approximately 200,000 af/year (Schmidt et al., 2016). CRSS does not include this ‘salvage’ evaporation volume in the mass balance for Lake Powell, but Reclamation justifies the use of this administrative procedure by applying the same ‘net evaporation’ method when calculating the naturalized inflows. This effectively tries to incorporate this ‘salvage’ evaporation volume into a generalized channel loss in the naturalized inflow data immediately upstream of Lake Powell. However there is no certainty that historical ‘salvage’ evaporative losses would be equal to future losses since reservoir levels differ between the calculation of naturalized flows and predictions into the future. Furthermore, if hydrologic inflows are not derived directly from, or calibrated using, the naturalized flow data set, the ‘net evaporation’ method is likely not appropriate.

Evaporation at Lake Mead is precisely measured using state-of-the-science methods; data have been published for the period between 2010 and 2015 (Moreo, 2015), and release of data for subsequent years is anticipated. A state-of-the-science program for measuring evaporation from Lake Powell was initiated approximately two years ago, and data have not yet been published. Wang and Schmidt (2020) demonstrated that there is large uncertainty in applying the present estimates of Lake Powell evaporation used in CRSS in the calculation of a water budget for that reservoir. Despite the large uncertainty in estimating total evaporation from Lakes Mead and Powell, the total evaporation losses of the two major reservoirs is an important water-supply metric in the evaluation of alternative management paradigms. For this study, we use the combined evaporation volume from Lake Mead and Lake Powell from CRSS as the primary metric for system losses, which consistently ignores the approximate 200,000 af/year salvage volume from Lake Powell.

Energy Generation

Although improving the reliability of water supply and providing flood control are the primary objectives of the storage infrastructure in the Colorado River Basin, production of hydroelectricity has always been an essential rationale for building the large dams and, once built, the operation of these dams for power purposes has become an important factor. The Boulder Canyon Project Act required that contracts to purchase hydroelectricity generated at the dam had to be sufficient to pay off the dam before construction could begin. The dams authorized by the CRSP Act are widely referred to as ‘cash register dams,’ because the revenue from the sale of hydroelectricity from those dams is the revenue that supports the Colorado River Basin Fund. Revenues from this fund subsidized the construction of many agricultural irrigation projects and some transbasin diversions. Today, power revenues fund project repayment, project operations and management, project replacements, and environmental programs; thus, power generation is a useful metric due to the electricity produced and the financial resources they provide.

Marketing of federally produced power in the Colorado River Basin has been the responsibility of the Western Area Power Administration since the late 1970s when the Department of Energy was created. The Western Area Power Administration makes recommendations to Reclamation concerning the months, days, and hours when electricity can be sold for the greatest revenue return to the federal treasury. Nevertheless, power production at most large dams is restricted by environmental considerations that limit the range of daily hydropeaking and the instantaneous rate of change of those flows.

The CRSS model calculates energy generation from each major reservoir as a byproduct of the releases through the powerplant and the elevation of the reservoir. Because the monthly time step of CRSS, sub-monthly operations, such as peak power production, are not described by the model. The Western Area Power Administration uses a proprietary program, GTMax, to downscale monthly reservoir operations predicted by CRSS to consider aspects of power operations that are concerned with daily and hourly power production. We did not make an effort to predict sub-monthly aspects of power generation, and estimated monthly energy generation based on methods of CRSS. We reported our analysis as exceedance plots. Although Hoover and Glen Canyon Dam electricity production is marketed to different regions, we aggregated monthly generation at Glen Canyon and Hoover to provide a regional perspective of the energy implications of modifying the operations of these two reservoirs.

8.2 Ecosystem Driver Metrics

Ecosystem drivers are abiotic attributes, such as flow regime, temperature, or sediment dynamics, that determine ecosystem structure and function. Changes in ecosystem drivers could potentially result from any of the three general types of alternative management paradigms described in Section 4—changes in consumptive water use that deplete or augment streamflow, changes in reservoir operations that change the flow regime without necessarily changing the total annual flow, and changes in infrastructure. In turn, changes in ecosystem drivers have the potential to cause changes in ecosystem attributes such as persistence of threatened or endangered species, non-native trout that are of recreational value, or native riparian vegetation, including cottonwood gallery forests.

We sought to predict changes in ecosystem drivers rather than in ecosystem attributes. In many cases, there is significant uncertainty in predicting how ecosystem attributes might change in response to changes in ecosystem drivers. This uncertainty arises from the complexity of ecosystem responses to changes in these drivers. For example, we know flow regime is an important determinant of fish community structure due to differing life histories of fishes. Thus, flow regime is an important determinant of the relative abundance of native versus non-native fish. We know less, however, about the outcome of interactions between native and non-native fish when a stream's flow regime changes. Subsequent work seeks to predict the effects of ecosystem drivers on fish communities, but these types of changes are not included here.

There are many ecosystem drivers that may be influenced by future climate conditions and alternative management paradigms, and these metrics are more extensively explored by Schmidt, Bruckerhoff et al. (in prep). Here, we considered metrics describing two ecosystem drivers, flow regime (alteration index) and temperature (reservoir release temperatures and a temperature threshold for maintaining a trout fishery), as examples of how the ecosystem outcomes of alternative management paradigms can be evaluated.

Flow Regime

Flow regime describes the magnitude, frequency, duration, temporal sequence, and rate of change of streamflow. These attributes may differ from year to year, especially between years of large and small runoff. Because flow can vary across a wide range of temporal scales (from minutes to decades), there are many metrics that can be used to describe flow variability across these different temporal scales. Extreme flow events, such as droughts or floods, are of particular interest from a water supply perspective. Many statistical approaches have been developed by hydrologists and water resource engineers to characterize flood hazards or the risks to water supply caused by droughts.

Flow is often considered the 'master' variable driving riverine ecosystem processes (Power et al., 1995; Sofi et al., 2020). The linkages between aspects of flow regime and ecological processes are well described in general (Doyle et al., 2005) and for the Colorado River Basin (Poff et al., 1997). For example, several studies demonstrated that changes in the flow regime adversely affected native ecosystems through changes in species composition of native aquatic macroinvertebrates (Vinson, 2001; Kennedy et al., 2016), dominance of non-native fish species (Gido and Propst, 2012), and changes in riparian vegetation (Turner and Karpiscak, 1980; Sankey et al., 2015). In addition to these biotic responses, abundant literature has described changes in channel form and habitat throughout the Green River, and many of these changes have been caused by reservoir operations at Flaming Gorge (Grams and Schmidt, 2005; Dean et al., 2020; Walker et al., 2020).

Alteration Index

We defined a metric that quantifies the degree to which regulated monthly flows differ from the natural flow regime. Although aspects of flow regime can be described using various temporal scales, we chose monthly flows because water supply considerations are often considered at the monthly time step used in CRSS. This ‘Alteration Index’ is based on comparing the monthly flows predicted by our modeling runs to the monthly flows characteristic of pre-dam conditions. Nevertheless, we recognize that many shorter time scale aspects of flow regime are of critical concern to the life history of many species.

In the Upper Basin, we define the pre-dam period as between 1930 and 1960, before construction of the Colorado River Storage Project (CRSP). We considered pre-CRSP flows for the period beginning in 1930, and we did not consider the period of large runoff that occurred in the early 20th century pluvial period (Salehabadi et al., 2020). By considering this period, we aimed to capture average pre-dam conditions that were also less impacted by climate change compared to current flow conditions. We tabulated each month's flow for each year and calculated the values of monthly runoff that were exceeded in 25%, 50%, and 75% of years (percentiles).

We then defined the Alteration Index as the ratio of the predicted 25th, 50th, and 75th percentile of monthly predicted flows across all years to the same percentiles of monthly flows during the pre-dam period described above. In other words, we divided the 25th percentile of the predicted flows by the 25th percentile of the pre-dam flows, and the median predicted flows by the median pre-dam flows and so forth. Because each management alternative with a particular hydrologic scenario was analyzed in CRSS using multiple hydrologic traces (see Section 6 above), we reported the interquartile range across the traces for the three levels of the Alteration Index (25th, 50th, and 75th percentiles across years). The further this index is from 1, the more altered the flows are considered to be.

To illustrate, we calculated the Alteration Index for the interquartile range of post-dam flows for the period 1990-2015. Figure 8.3 shows how flow regimes have been greatly altered for the Colorado River at Lees Ferry where the Alteration Index ranges from 0.1 to 3. Values less than 1 mean modern flows are less than those of the past and values greater than 1 reflect an increase in modern flows in relation to those of the past. This index is proportional, so an Alteration Index value for high flows of 2 represents modern flows that are twice the magnitude of historic high flows and a value of 0.5 would represent high flows that are half the magnitude of historic high flows.

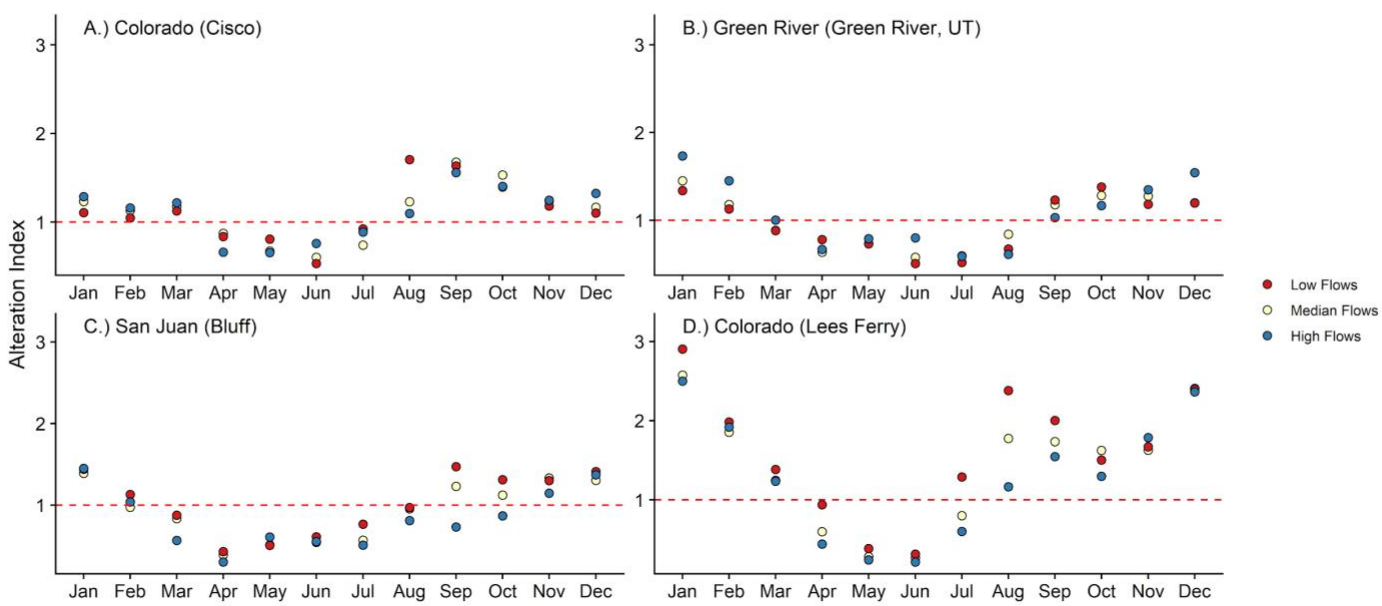

Figure 8.3 .Graphs showing the Alteration Index for each month for four gages in the Colorado River watershed, Colorado River near Cisco (A), Green River at Green River (B), San Juan River near Bluff (C), and Colorado River at Lees Ferry (D).

Temperature

Reservoir release temperatures are an important determinant of downstream river temperatures. Temperature is a fundamental driver of ecosystem structure, because river temperature creates habitats suitable for different species. River temperature also controls ecosystem processes such as primary productivity, ecosystem respiration, nutrient dynamics, resource availability, and species growth rates. Thus, reservoir release temperature is a significant control on the ability of different species to persist downstream from dams. For example, species tolerant of cold water, such as rainbow trout and brown trout, are common in cold-water zones immediately downstream from dams. Native species have been pushed out of these reaches.

River temperatures are closely linked with decisions about water-supply management, because reservoir elevation is a strong driver of reservoir release temperatures (Dibble et al., 2020). Large reservoirs thermally stratify, and water released through penstocks deep below the water surface is typically cool in summer (Figure 8.4). For example when Lake Powell is relatively full, water is released at an elevation approximately 200 ft below the water surface and average year round water temperatures are 7° C. This is dramatically lower than the pre-dam yearly average water temperature of 26° C. Whenever reservoir storage is reduced, water is released from shallower depths and is typically warmer.

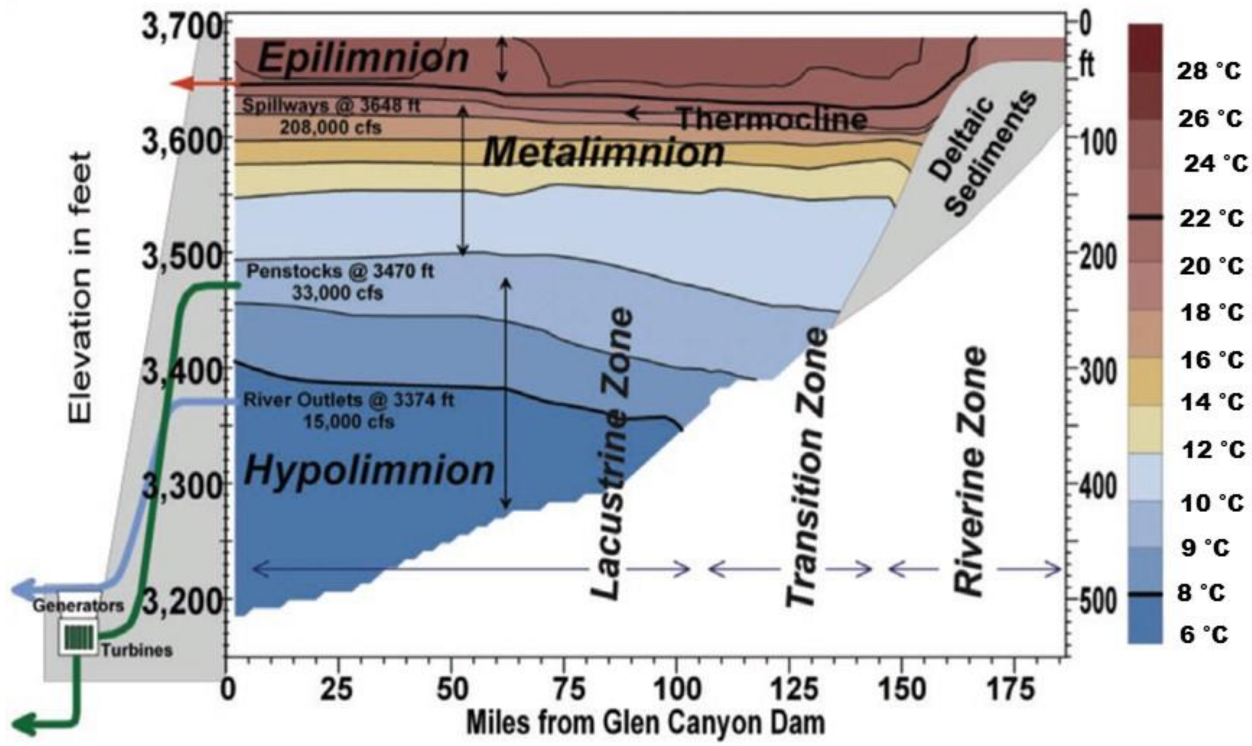

Figure 8.4. Thermal stratification in Lake Powell. Release temperatures are driven by pool elevation because as pool elevation decreases, warmer water layers are released through the penstocks (Vernieu, 2005).

Predicting ecosystem responses to temperature is complex. Even species-specific responses to temperature are dependent on a wide variety of factors such as exposure timing (time of year), length of exposure (length of time in which temperatures exceed some physiological threshold), and acclimation (long term exposure) time and temperature. Further, different temperature ranges may be limiting for different physiological responses (growth, survival, reproduction) at different life stages (egg, larvae, adult).

Due to these complexities of predicting ecosystem responses to temperature, we limit our discussion in this paper to comparing predicted temperatures to temperatures observed since the construction of Glen Canyon Dam, and we do not define optimal temperatures for native Colorado river species. Because there is less uncertainty associated with the upper temperature limits of rainbow and brown trout species, we do discuss whether or not future temperatures would be suitable for maintaining tailwater trout fisheries. Further, we only consider metrics related to reservoir release temperatures. We focus on release temperature, because it is ecologically relevant due to its role in driving downstream river temperatures.

Reservoir Release Temperature and Volume

We considered both release temperatures and release volumes together, because release volumes are a strong determinant of the effect on downstream river temperatures (Wright et al., 2009; Mihalevich et al., 2020; Dibble et al., 2020). We compared predicted release temperatures and release volumes to historic variation in release temperatures and volumes and the associated downstream river temperatures in the Colorado River at Lees Ferry, near the Little Colorado River, and near Diamond Creek. We chose these three locations, because they represent a gradient of temperature change from Glen Canyon Dam to Lake Mead and because these locations represent ecologically important places alongs the river. The tailwater trout fishery is located around Lees Ferry, while the Little Colorado River is an important tributary for humpback chub populations. Diamond Creek is located in western Grand Canyon where there have been recent increases in the relative abundance of native fishes.

We focused on summer temperatures (June through September), because summer is the critical season for growth and reproduction of many species and because summer temperatures are highly sensitive to future climate conditions and water management decisions.

We used the distribution of observed release temperatures, volumes, and river temperatures from 1989 through 2020 for the Colorado River at Lees Ferry (Figure 8.5) as a point of reference with which to compare predicted combinations of release temperatures and volumes. We used simple relationships among river mile, volume, and release temperature to plot approximate mean temperature conditions at each location based on models developed by Dibble et al. (2020). The predicted temperatures do not account for future climate conditions and important physical drivers of river temperatures as water moves downstream. Predicted river temperatures based on models that account for the rate in which river water warms as it moves downstream is presented in Wright et al. (2009), Mihalevich et al. (2020), and Schmidt, Bruckerhoff et al. (in prep). The river temperature prediction displayed in this paper only serves to help visualize and compare predicted temperature to current conditions. This ecosystem metric of temperature therefore included qualitative comparisons of future release temperature and volume combinations to historic release temperature and volume combinations.

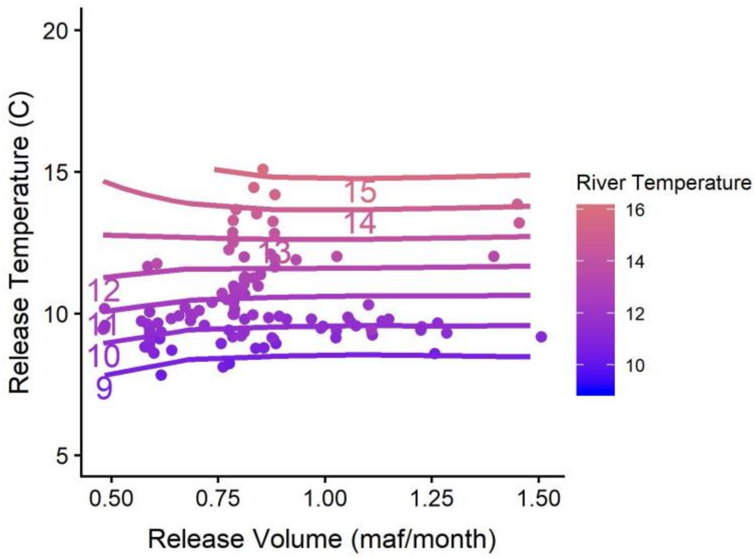

Figure 8.5. Release volumes and temperatures measured below Glen Canyon Dam and corresponding observed downstream river average summer temperatures (June, July, August, and September) of the Colorado River at Lees Ferry. Colored lines represent loess smoothing curves developed from observed river temperatures (points) for given combinations of discharge and temperature.

Temperature thresholds to maintain trout fisheries

There is one ecological outcome that can be predicted with confidence—the Grand Canyon will no longer be able to maintain a trout fishery if average reservoir release temperatures exceed 19°C. While trout can survive acute (short term) exposure of temperatures up to 29°C (Rodgers and Griffiths, 1983; Currie et al., 1998), recent studies suggest longer term (weekly) temperature means above 19°C constrain distributions of rainbow and brown trout (Mandeville et al., 2019). To be conservative, we define a threshold of average monthly release temperatures above 19°C to no longer be suitable to maintain the trout fishery. The metric capturing the ability to maintain a trout fishery is the probability that summer temperatures (June through August) would be above the 19°C threshold each year.

Sidebar 1:

How does water storage in Lake Powell influence release temperatures and Grand Canyon fishes?

by Dr. David Rosenberg, Utah Water Research Laboratory, and Dr. Lindsey Bruckerhoff, Postdoctoral Fellow, Center for Colorado River Studies

Objective

Analysis of Lake Powell release temperature and depth-temperature profile data can be used to identify ranges of reservoir water surface elevations that produce different temperature ranges at a monthly scale. We can use this analysis to determine whether future reservoir water surface elevations would produce reservoir release temperatures outside of the ranges that have been historically observed, which would result in highly uncertain impacts on ecosystems downstream of Glen Canyon Dam. We can also use this analysis to determine the range of reservoir water elevations that would not be suitable for maintaining the Grand Canyon trout fishery.

Results and Implications

Water levels in July, August, September, and October above 3,675 ft msl will give cold releases less than 12^{o}C (Figure A, dark blue bars). Water temperatures during these months are particularly important for many species' growth, reproduction, and survival of early life stages. Temperatures below 12^{o}C are within the range that have been observed in the past (Figure 8.5), but these cold releases during the growing season have been associated with native fishes being predominantly pushed into tributary and downstream habitats. Summer water levels between 3,600 and 3,675 ft msl will keep release temperatures between 12 and 15^{o}C (Figure A, light blue bars). Sustained release temperatures above 12^{o}C are historically rare, but have become more frequent since 2005. These warmer release temperatures and corresponding warmer river temperatures may be contributing to increased relative abundance of native fishes in western Grand Canyon, but other factors also likely contribute to these trends (Kegerries et al., 2020). August to October water levels below 3,600 ft msl will warm releases up to 18^{o}C (Figure A, pink bars). Here, outcomes are highly uncertain for native fish, as these temperatures have not been observed since the construction of the Glen Canyon Dam. Native fish may benefit, but they may also face invasion by warm water non-natives from Lake Mead. Lastly, July to August water levels below 3,525 ft msl will warm releases above 18^{o}C. These warm temperatures represent the highest level of uncertainty for native fish, but also represent a substantial risk to the tailwater trout fishery, as sustained temperatures of 19^{o}C or higher are unsuitable for trout. These high temperatures would be reached during the summer even if the Upper Basin States maintain their drought contingency plan target of 3,525 ft msl. If managers forgo turbine releases and release water through the river outlets, a similar stacked bar plot can be constructed that shifts water surface elevations down by 100 to 125 feet.

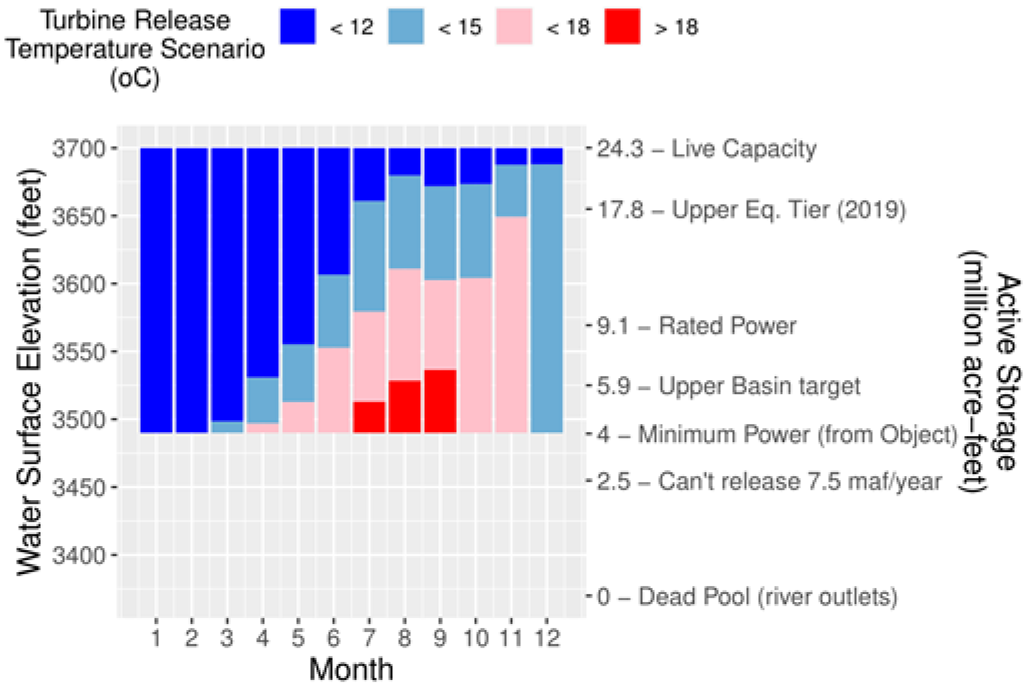

Figure A. Lake Powell water levels for turbine release temperature scenarios. Elevation ranges consider uncertainty in observed release and water profile data.

These results can help construct Fill Mead First and Fill Powell First alternative management paradigms (AMPs). For example, the elevations of 3,600 and 3,675 ft msl (light blue bars) can be used to set the Powell-Low and Powell-High parameters so release temperature more frequently stays below 15°C. Additionally, AMP elevation targets could be defined seasonally or monthly rather than annually to focus on summer months when release temperatures have the potential to be the highest. See Appendix 2 and Rosenberg (2020) [d1] for data, code, and further information.

[d1]Rosenberg, D. (2020). Colorado River Futures - Code Projects: How much water to store in Lake Powell to benefit native fish of the Grand Canyon? Utah State University. Logan, Utah. https://github.com/dzeke/ColoradoRiverFutures/tree/master/LakePowellTemperatureScenarios

9. Modeled Alternative Management Paradigms

Waters supply, hydropower, and ecosystem outcomes were analyzed for five alternative management paradigms (see Table 4.1). These alternatives were appropriate for further analysis because the alternatives could be precisely described, and the available modeling tools were useful to assess the water supply and ecosystem implications of each alternative. The analysis of these five alternatives also sheds light on other alternatives that are complimentary or similar.

Although each of the alternatives could be analyzed using any of the hydrologic scenarios presented in Section 6 or any of the Upper Basin depletion scenarios presented in Section 7, the magnitude of such a comprehensive analysis was beyond the scope of this investigation. We evaluated each alternative within the context of a select set of hydrologic scenarios and within the context of different Upper and Lower Basin demand scenarios (Table 9.1). We chose the hydrologic scenarios based on our interest in evaluating the performance of the alternatives under continued or dryer conditions.

	AMP Name	Hydrologies Considered	Upper Basin Demands	Lower Basin Demands	Prerequisite AMP
I.A	Combined Storage for Lower Basin Shortage Conditions	DNF 2000 Resample 1576 Resample RCP45_065 RCP85_100	2007 UCRC 3.0 maf Cap 3.5 maf Cap 4.0 maf Cap 4.5 maf Cap	Status quo Increased Shortages	None
II.A	Fill Mead First (FMF)	DNF 2000 Resample 1576 Resample	2007 UCRC	Status quo	I.A
II.B	Fill Powell First (FPF)	DNF 2000 Resample 1576 Resample	2007 UCRC	Status quo	I.A
II.D	Grand Canyon Engineered Flood Flows	DNF 2000 Resample 1576 Resample	2007 UCRC	Status quo	None
III.A	Flaming Gorge to Powell Backup	DNF 2000 Resample 1576 Resample	2007 UCRC	Status quo	None

Table 9.1. Selected alternative management paradigms for further modeling analysis

9.1 Evaluation of Alternative I.A: Using Combined Mead-Powell Storage to Determine Lower Basin Shortage Conditions

We evaluated an alternative management paradigm in which the combined water storage in Lake Mead and Lake Powell is established as the primary water management benchmark when large-scale water use conservation must be implemented. The concept of ‘conservation before shortage’ was proposed by a consortium of NGOs during the development of the 2007 Interim Guidelines, and the negotiators acknowledged the need to reduce water use when the incoming supply and stored volume greatly decreases. The negotiators defined benchmarks along quantifiable metrics that would trigger reductions in the amount of water supplied to the Lower Basin and Mexican water users when reservoir water storage becomes critically low. In the 2007 Interim Guidelines, the Lower Basin DCP, Minute 319, and Minute 323, the metric chosen was the elevation of Lake Mead. We examined an alternative paradigm in which the combined storage in Lake Mead and Lake Powell is considered as one integrated unit and in which the volume of storage, rather than the elevation of each reservoir, is the metric used. This alternative is similar to current practice in that water conservation becomes increasingly important as water supplies decrease.

The use of combined storage as a metric transparently reveals the impact of severe sustained drought and progressive decrease in watershed runoff on the total water supply and shows the tradeoffs between Upper Basin use caps and Lower Basin shortages necessary to maintain a sustainable level of storage. We used this metric to evaluate what combination of Upper Basin caps and Lower Basin (plus Mexico) shortages will result in sustainable combined reservoir levels under the stress of extended drought or aridification. Reducing the water delivered or available for use during times of drought is generally referred to as 'shortage.' In the parlance of Colorado River water-supply management, the word 'shortages' means the amount of water delivered to a Lower Division state or Mexico that is less than would be the case under the traditional 'normal' water supply conditions.

For purposes of analysis, we defined a three-tiered benchmark using the combined storage metric wherein the shortage increases as the amount of water stored in the reservoirs declines. The benchmarks associated with each tier could be different from the ones proposed here, and our intention is to illustrate the utility of a tiered approach to implementing cutbacks associated with a metric that considers the combined storage of the two largest reservoirs on the Colorado River.

In developing this alternative (hereafter referred to as Alternative 1.A), we first asked, **“Can a tiered strategy for implementing reductions in water use based on a metric of the combined storage contents of Lakes Mead and Powell be implemented in a way that is consistent with current management practice?”** To make this assessment, we established benchmarks defining three tiers comparable to particular tiers and shortages defined in the Interim Guidelines, DCP, and Minute 323 which are 0.613, 1.013, and 1.375 maf/year when the elevation of Lake Mead is at 1075, 1045 and 1025 ft msl, respectively (Table 2.1). These elevations correspond to 36%, 27%, and 22% of Lake Mead’s capacity. The combined storage volume benchmarks we defined in Alternative 1 are approximately the same: 21.0 maf, 16.0 maf and 11.0 maf (Table 9.2) and correspond to 42%, 32%, and 22% of total available storage in Lakes Mead and Powell.

Shortage Tier	Combined Storage Range (maf)	Arizona (maf)	Nevada (maf)	California (maf)	Mexico (maf)	Total Lower Basin Shortage (maf)
Tier 1	21 > Storage > 16	0.512	0.021	0	0.080	0.613
Tier 2	16 > Storage > 11	0.640	0.027	0.200	0.146	1.013
Tier 3	Storage < 11	0.720	0.030	0.350	0.275	1.375

Table 9.2. Combined storage tiers and applied shortages to the Lower Basin and Mexico for Alternative 1. This alternative seeks to match average shortages under the existing management when considering the *DNF* hydrology

The magnitude of shortages initially implemented in Alternative 1.A are comparable to those implemented in existing agreements, indicating the combined storage in Lake Mead and Lake Powell is a viable metric that could be used for declaring Lower Basin Shortage conditions. We reached this conclusion based on comparing the predicted shortage that arises from implementing Alternative 1.A with the predicted outcome of current management practice. We made this comparison based on using the same hydrologic scenario and the same assumption of progressively increasing Upper Basin water use. Thus, we used the current configuration of CRSS and the DNF (1906-2018) hydrologic scenario (Figure 9.1). The reader should remember the DNF (1906-2018) hydrologic scenario assumes all recorded hydrologic conditions have an equal probability of occurrence, including the extremely wet conditions of the early 20th century pluvial period which is unlikely to occur in the future. Furthermore, the current configuration of CRSS assumes Upper Basin consumptive water use continues to increase based on the projections made by the UCRC in 2007. We demonstrated in Section 6 that these Upper Basin consumptive uses are unlikely to ever occur. We compared the average shortages that would occur under the optimistically wet DNF (1906-2018) hydrologic scenario, the aspirational assumptions of continued growth of Upper Basin consumptive water use, and the agreements that implement Lower Basin shortages. We compared the magnitude of predicted shortages using the tiers identified in Table 9.2 and using the benchmarks of Lake Mead elevations. The two approaches are comparable, because the black and red lines in Figure 9.1 are approximately the same.

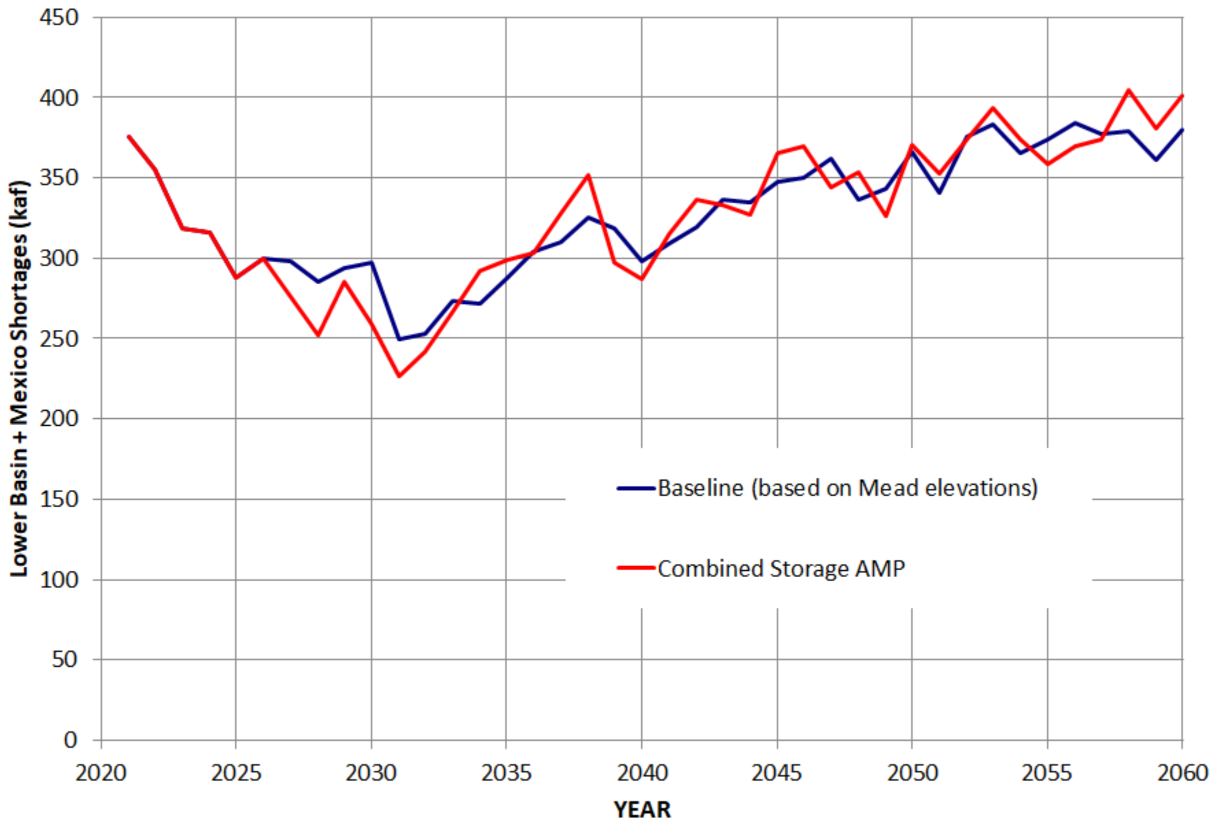

Figure 9.1. Average Lower Basin + Mexico shortages with combined storage benchmarks using the DNF hydrology and the 2007 UCRC future depletion schedule. Baseline indicates current operations under 2007 Interim Guidelines, DCP and Minute 319 and 323.

These model runs predict an initial increase in total storage in Mead and Powell for the period between 2021 and 2030, because the average assumed inflow to the Powell-Mead system exceeds the Lower Basin demands and evaporation losses during this period (Figure 9.2). As soon as the future inflows resulting from the DNF hydrologic assumption are less than the assumed downstream demands and losses (i.e., what occurs after 2030 in Figure 9.2), the models predict a steady decline in combined reservoir storage. This steady decline in Lake Powell inflows, and hence combined storage, is caused exclusively by the assumed progressive increase in Upper Basin consumptive water use. It is significant that reservoir storage is predicted to decline despite the fact that the assumed DNF hydrology includes traces with unlikely high inflows. Progressive depletion of reservoir storage is not a sustainable water management strategy.

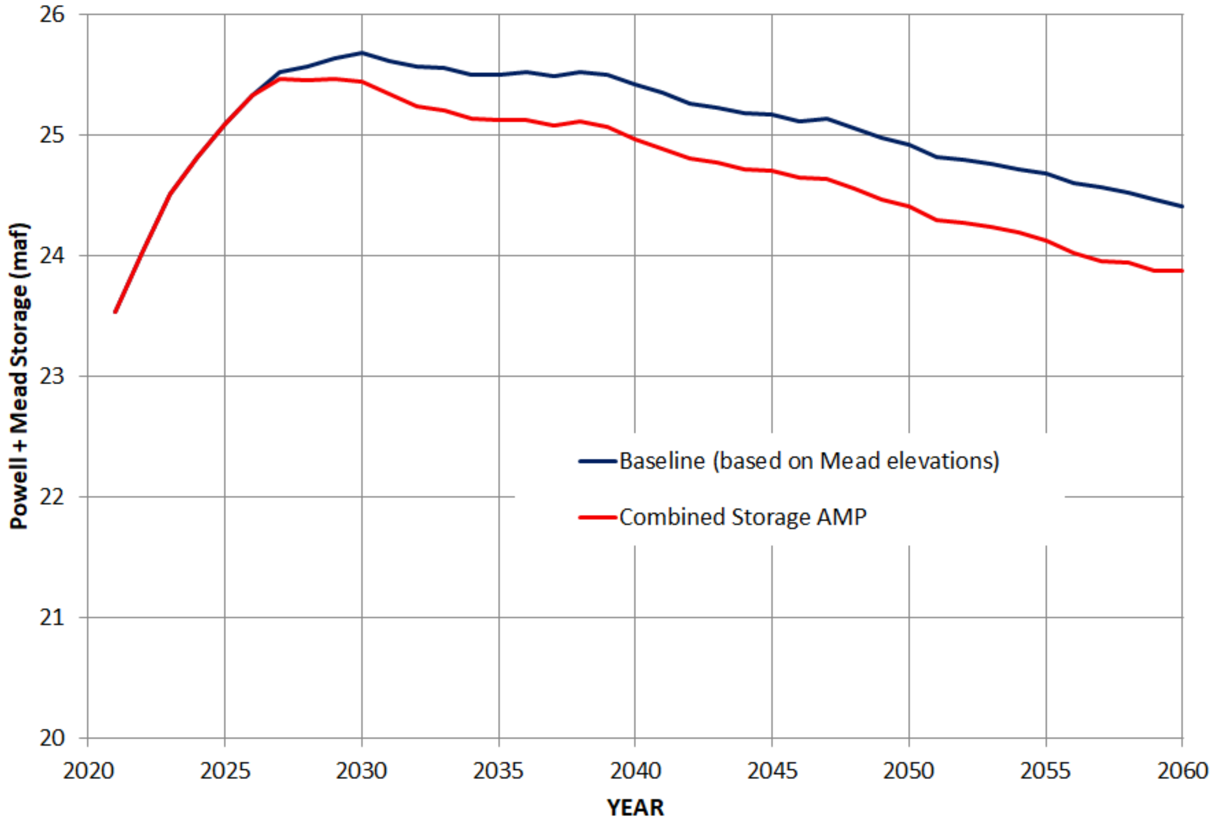

Figure 9.2. Average end-of-year combined storage using combined storage benchmarks with the DNF Hydrology. Baseline indicates current operations under 2007 Interim Guidelines, DCP and Minute 319 and 323.

We next asked, **"What is the magnitude of consumptive use that can be sustainably maintained during drought conditions?"** We evaluated this question by simulating various combinations of Lower Basin shortages and 'caps,' or limits on future growth in water use, in the Upper Basin. This analysis assumes the Upper Basin has no compact obligations, thus the results presented here should be viewed with those shown in Section 7. We adjusted the benchmarks that defined the tiers of Lower Basin shortages to initiate shortages for the Lower Basin States and Mexico earlier than the present strategy (Table 9.3). Shortages are assumed to be initiated when combined storage is less than 25 maf (50% of total capacity) for Tier 1, less than 20 maf (40% of total capacity) for Tier 2, and less than 15 maf (30% of total capacity) for Tier 3. Our goal was to evaluate the amount of Lower Basin and Mexico shortages necessary to achieve system sustainability, so for Tier 3, we use CRSS to test the implications of a range of total shortages from 1.375 maf to 3.0 maf. The shortage was distributed somewhat arbitrarily across the Lower Basin States and Mexico to achieve the total shortage objective (X1 through X4 in Table 9.3) and allow the system sustainability to be assessed.

For the Upper Basin, we evaluated a wide range of projections of future use from continued growth as projected by the 2007 UCRC demand schedule to a limit of 3.0 maf/year. We assumed the Upper Basin consumptive uses were in lieu of any compact obligations at Lee Ferry. We did not consider it necessary to define which specific users would limit their consumption.

Shortage Tier	Combined Storage Range (maf)	Arizona (maf)	Nevada (maf)	California (maf)	Mexico (maf)	Total Lower Basin Shortage (maf)
Tier 1	25.0 > Storage > 20.0	0.512	0.021	0	0.080	0.613
Tier 2	20.0 > Storage > 15.0	0.640	0.027	0.200	0.146	1.013
Tier 3	Storage < 15.0	X1	X2	X3	X4	Y

Table 9.3. Combined storage tiers and variable Lower Basin shortages applied to CRSS to explore the implications of droughts and climate change, and seek system stability.

Similar to previous results, a **continued unconstrained increase in Upper Basin consumptive water uses is not sustainable under severe and sustained drought**, such as is represented in the hydrologic scenario of the current Millennium Drought (2000 Resample). **Likewise, shortages to the Lower Division states and Mexico will need to be greater than 1.375 maf to achieve sustainability.** The status quo (red line) reflects the average of the model runs, and combined water storage in Mead and Powell progressively decreases during a 20-year period until both reservoirs are at approximately dead pool (Figure 9.3). The projection reflected in the red line assumes continued increase in Upper Basin consumptive use following the projections of the UCRC (2007).

The reader is encouraged to examine Figure 9.3 to evaluate the various combinations of reduction in projected growth in Upper Basin water use, and reduction in Lower Basin use when the combined Mead-Powell storage is in Tier 3. **These results demonstrate that the Colorado River water supply can be sustainably managed, even during extreme drought, if future growth in Upper Basin water use is limited, and significantly larger shortages are applied to the Lower Basin States and Mexico than what are currently specified.**

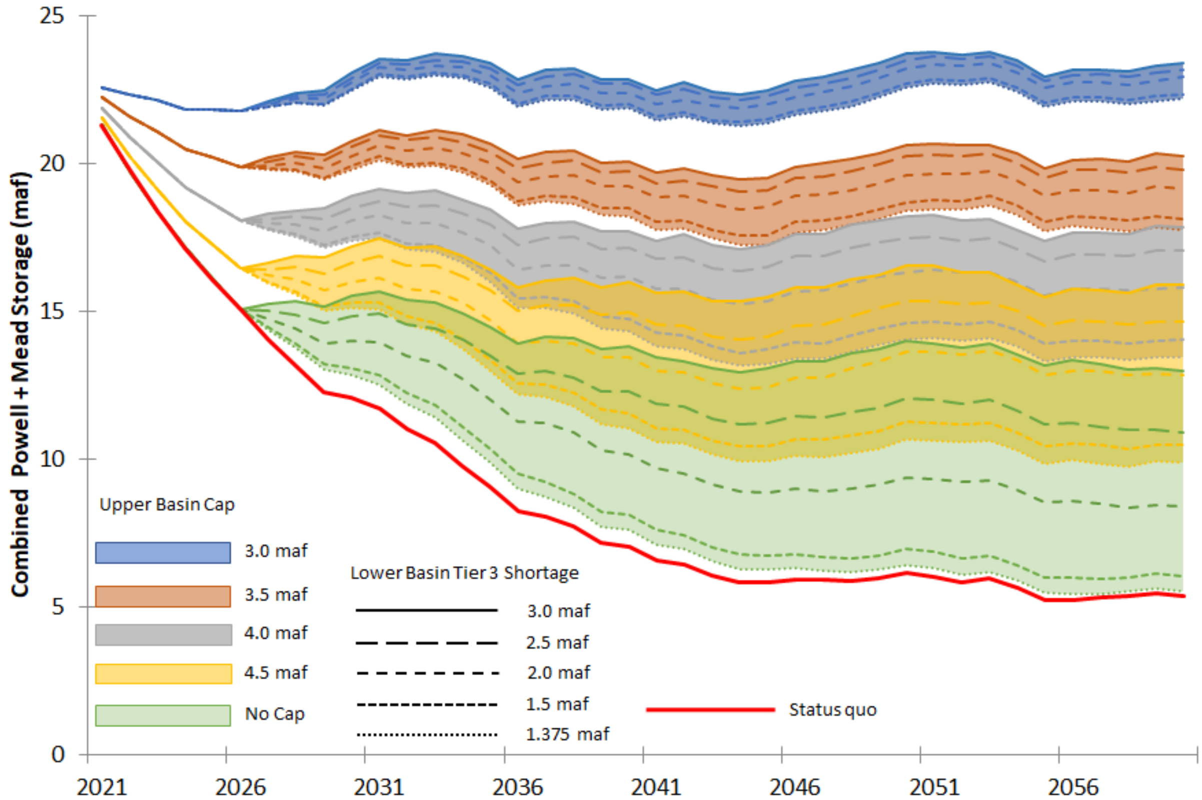

Figure 9.3. End-of-year combined Lake Powell + Lake Mead storage using 2000 Resample hydrology, demonstrates a range of Upper Basin demand 'caps' along with a range of Lower Basin maximum (i.e. Tier 3) shortages. Status quo uses the 2007 UCRC Upper Basin schedule and elevation-based shortage triggers.

We reached a similar conclusion regarding the effort needed to achieve sustainable water-supply management under the Paleo Tree Ring Drought (1576 Resample) hydrologic scenario (Figure 9.4). If such a drought were to occur and Upper Basin water use were to continue to increase, the total storage in Mead and Powell would fall below 10 maf within a decade.

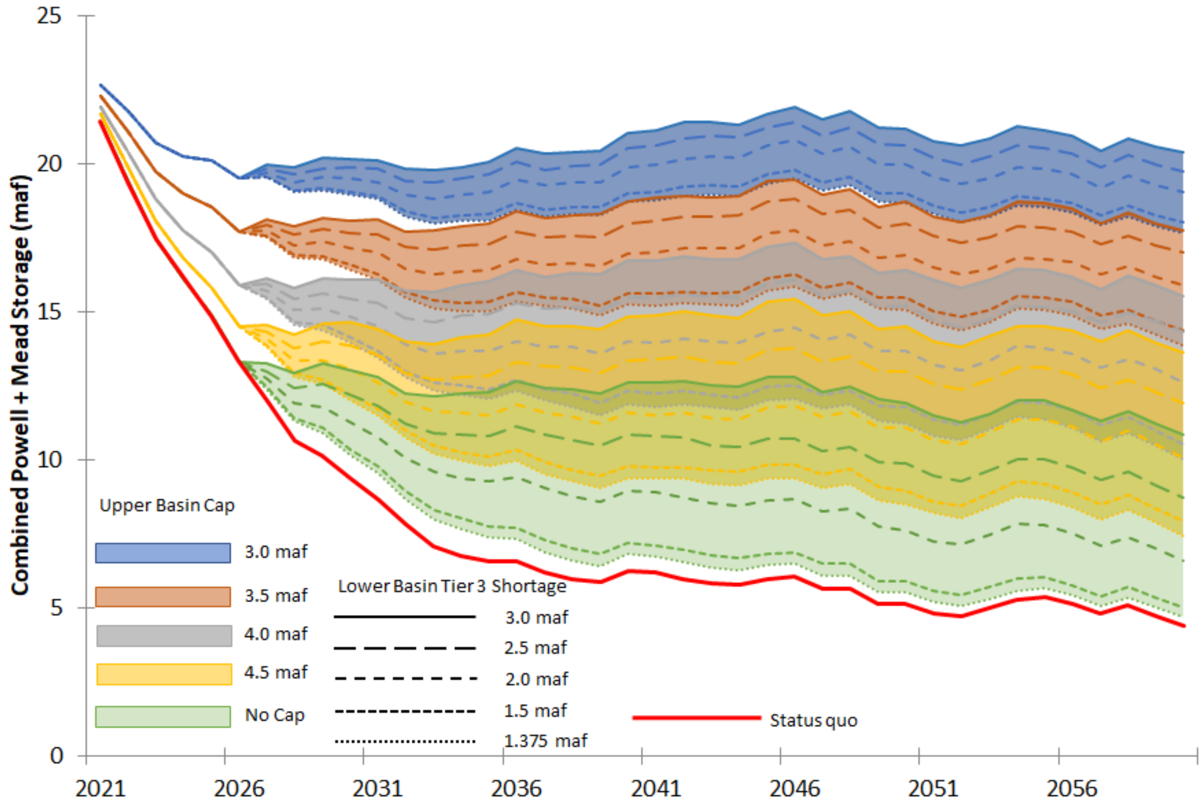

Figure 9.4. End-of-year combined Lake Powell + Lake Mead storage using 1576 Resample hydrology, demonstrates a range of Upper Basin demand 'caps' along with a range of Lower Basin maximum (i.e. Tier 3) shortage commitments. Status quo uses the 2007 UCRC Upper Basin schedule and elevation-based shortage triggers.

We reached a similar conclusion in analyzing the sustainability of the water supply under the current and growing stress of basinwide warming resulting in decreases in watershed runoff. This 'new abnormal' case suggests the current drought condition will worsen. As noted in Section 6, we consider the RCP4.5_065 hydrologic scenario to be the most probable climate change since it most closely matches the hydrologic conditions experienced over recent decades. In this scenario, radiative forcing stabilizes by 2100, and there is a 6.5% decrease in runoff with each degree Celsius of warming. Because the predicted climate change is progressive throughout the entire modeling period, the downward trend in total storage cannot be arrested, but the rate of decline can be ameliorated substantially by a combination of reducing Upper Basin uses and increasing Lower Basin shortages (Figure 9.5).

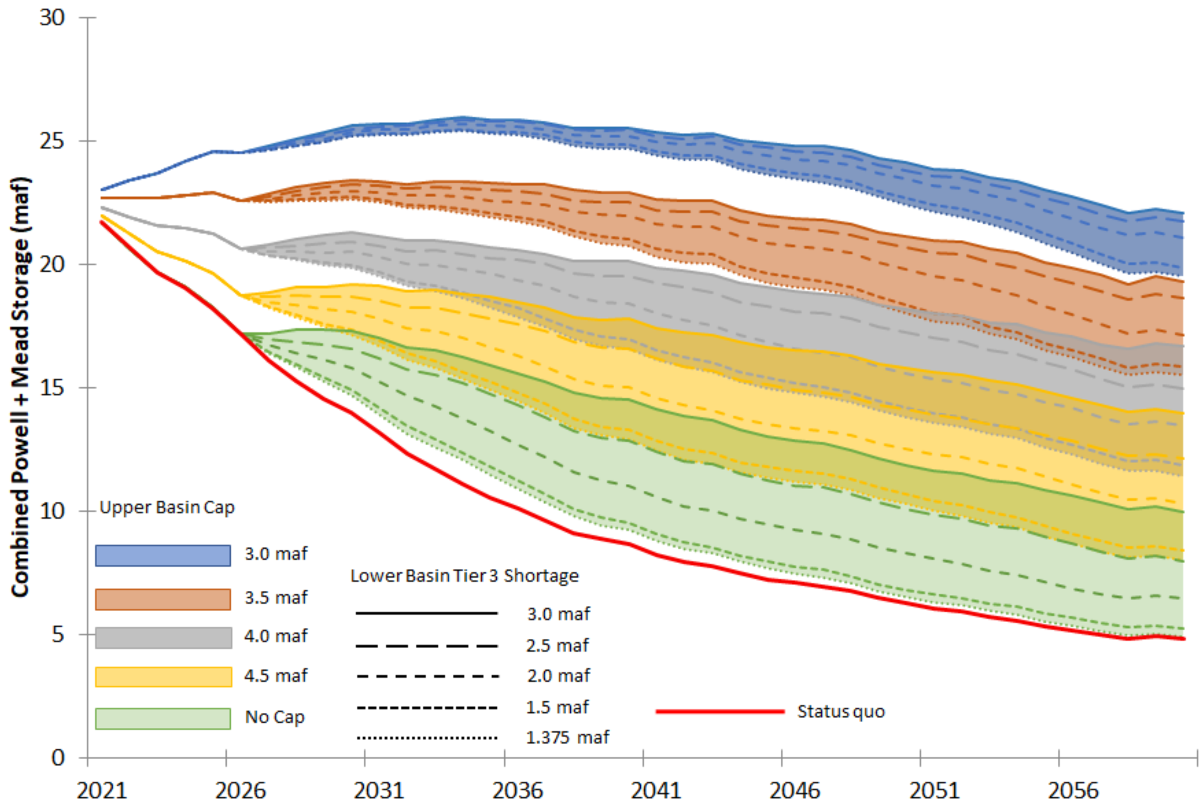

Figure 9.5. End-of-year combined Lake Powell + Lake Mead storage using RCP45_065 hydrology, demonstrating a range of Upper Basin demand 'caps' along with a range of Lower Basin maximum (i.e. Tier 3) shortage commitments. Status quo uses the 2007 UCRC Upper Basin schedule and elevation-based shortage triggers.

Under the most severe climate change scenarios (RCP8.8_100), the storage in the Colorado River system would become severely depleted. Following a high emissions scenario of RCP8.5 with a 10% decrease in runoff with each degree Celsius of temperature rise, even an Upper Basin cap of 3.0 maf/year and a commitment of the Lower Basin to reduce its uses by 3.0 maf/year is insufficient to sustainably manage the Colorado River system (Figure 9.6). If this scenario were to occur, major societal adjustment would need to occur.

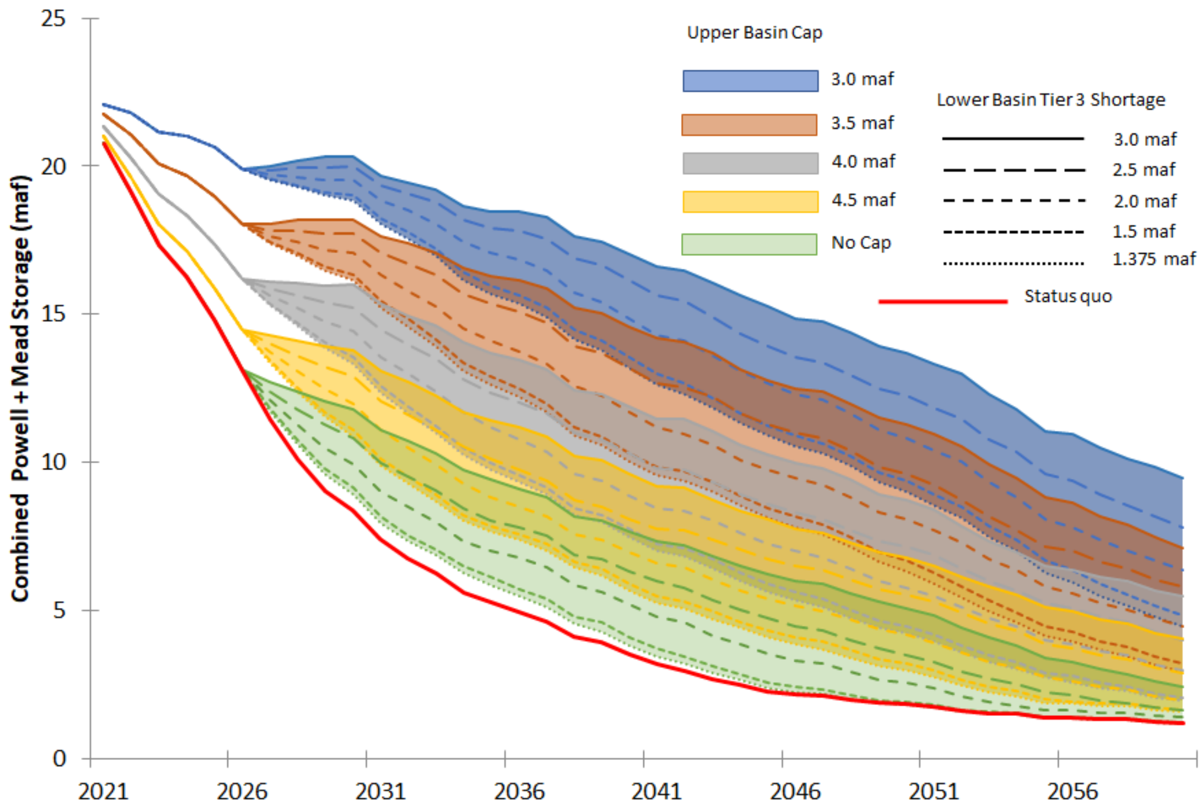

Figure 9.6. End-of-year combined Lake Powell + Lake Mead storage using RCP85_100 hydrology, and demonstrates a range of Upper Basin demand 'caps' along with a range of Lower Basin maximum (i.e. Tier 3) shortage commitments. Status quo uses the 2007 UCRC Upper Basin schedule and elevation-based shortage triggers.

Findings: Implementing Lower Basin shortages based on combined Lake Powell and Lake Mead storage provides a logical basis to make decisions regarding the sustainability of the system. In this analysis, we show the degree to which applying Upper Basin caps and increasing the maximum Lower Basin shortages improves the sustainability of the Colorado River system, particularly during a sustained drought or if the current conditions have actually become the 'new normal.' Plausible climate change projections will further stress the Colorado River system, such that it will be very difficult to maintain significant amounts of reservoir storage. **Implementation of Alternative 1.A, the use of the combined storage contents of Lakes Mead and Powell is a more effective metric to support management decisions. It both better reveals the actual risk to water supplies and allows identification of the potential solutions. The traditional Lower and Upper Basin approach that one is 'our reservoir' and the other is 'your reservoir' not only adds to a misunderstanding of the current state of the water supply system, but also obscures the possible solutions to confront the future risks of severe drought and climate change.**

Ecosystem Outcomes: This analysis reveals the likely impact of the status quo management under different hydrologic conditions, and how those risks could be managed. Reduction in reservoir storage contents in Lake Mead and Lake Powell to an extremely low level will inevitably cause profound ecosystem change in the Grand Canyon. Releases from Lake Powell would be sufficiently warm such that the existing novel fish community would change greatly (Dibble et al., 2020). The nature of these changes is not predictable, because the outcome of interactions between native and non-native fish are not known. The flow regime of the Colorado River in the Grand Canyon would also dramatically change whenever reservoir contents in Lake Powell fell below minimum power pool elevation, because the only way to release water would be through the river outlets (Schmidt et al., 2016). It is likely that the formation of sand bars might increase during severe sustained droughts because of the low transport capacity of the reduced flow regime.

Further downstream, less water would be available in the lower river to support the efforts by the Lower Colorado River Multi-Species Conservation Program to create new riparian habitat. Under the conditions of sustained drought and in the absence of significant reductions in consumptive water use, it will be extremely challenging to deliver water to the delta for environmental rehabilitation purposes. Reduced Upper Basin consumptive uses have the potential to ameliorate the impacts of drought in the Upper Basin because the water destined for Lower Basin water users remains in the channel network of the Upper Basin.

9.2 Evaluation of Alternative II.A: Fill Mead First (FMF)

The FMF alternative management paradigm would prioritize storage in Lake Mead and relegate Lake Powell as a secondary storage facility. Versions of this concept were first proposed in 2009 by the Glen Canyon Institute (GCI).The plan was clarified by Kellett (2013) and gained some attention in the popular literature (Beard, 2015; Lustgarten, 2015, 2016).

The objectives of the FMF plan are to:

- re-expose rapids of lower Cataract Canyon and Glen Canyon's sandstone walls;
- begin the process of re-creating a riverine ecosystem in Glen Canyon;
- restore a more natural streamflow, temperature, and sediment supply regime of the Colorado River in the Grand Canyon ecosystem;
- reduce water losses caused by evaporation and losses into groundwater storage.

The FMF plan as originally proposed by GCI would be implemented in three phases. Phase One would involve lowering Lake Powell to the minimum elevation at which hydroelectricity can be produced, (i.e., minimum power pool). At this elevation, the water surface area of Lake Powell is approximately 77 mi^2, which is 31% of the surface area when the reservoir is full. Phase Two of the FMF plan would involve lowering Lake Powell to dead pool elevation, abandoning hydroelectricity generation, and releasing water only through the river outlets. The water surface area of Lake Powell at dead pool is approximately 32 mi^2 and is 13% of the reservoir surface area when it is full. Implementation of Phase Three would necessitate drilling new diversion tunnels around Glen Canyon Dam in order to eliminate all water storage at Lake Powell.

General aspects of this alternative were evaluated by Myers (2013) and Schmidt et al. (2016), however, these analyses did not consider precisely how the FMF proposal would be implemented within the context of other elements of Colorado River management, nor did they analyze this proposal under a wide range of hydrologic conditions. These implementation nuances concern the need to protect critical storage levels in each reservoir and whether Lake Mead should be filled to maximum capacity before water storage in Lake Powell begins (see sidebar "How does water storage in Lake Powell influence release temperatures and Grand Canyon fishes?"). In this study, we considered an implementation of the FMF plan that allows Lake Powell to be reduced to the dead pool, subject to hydraulic limitations of the river outlets. Four variations to this Alternative Management Paradigm are considered.

We assumed maintenance of a minimum pool elevation in Lake Mead of 1,000 ft msl would be the highest priority of Colorado River management, hereafter termed Mead-Low. Under very low watershed runoff conditions when there is only a small amount of water available to be stored, that water would be preferentially stored in Lake Mead in *priority zone one*, which is defined as the zone above dead pool and below 1,000 ft msl in Lake Mead (Figure 9.7). Once Lake Mead is filled to 1,000 ft msl, additional water would be stored in Lake Powell in *priority zone two*, but only up to an predefined elevation, hereafter termed Powell-Low. We considered two different elevations for the top of *priority zone two*: 3,600 ft msl (variation A) and 3,500 ft msl (variation B). Both of these target elevations are above minimum power pool, thereby ensuring that hydroelectricity production would continue. Once *priority zone two* is filled, additional water would be stored in Lake Mead until the reservoir reaches the maximum elevation of *priority zone three*. We term this elevation Mead-High, and we considered two different elevations for the top of *priority zone three*: 1,200 ft msl (variation 1) and 1,135 ft msl (variation 2). In variation 1, Lake Mead has a comparatively wide range of operating space. The maximum elevation defined in variation 2 is the elevation we assumed to maintain fragmentation of Lake Mead from the Colorado River in western Grand Canyon. This is the approximate reservoir elevation at which Pearce Ferry Rapid remains as a significant rapid that is likely a barrier to warm water non-native fish in Lake Mead and that might compete or prey on native fish in western Grand Canyon. Although the role of Pearce Ferry Rapid in maintaining fragmentation is under investigation, we evaluated the water supply implications of maintaining this feature.

When *priority zone three* is filled, additional water would be stored in Lake Powell in *priority zone four*, up to the elevation of Powell-High. Because we assumed current operational rules concerning flood control at Lake Mead and Lake Powell will not be changed, implementation of these rules do not result in complete filling of either reservoir. We assumed current operational rules would determine the rate of releases from Glen Canyon Dam once Lake Powell was sufficiently full such that flood control was a concern.

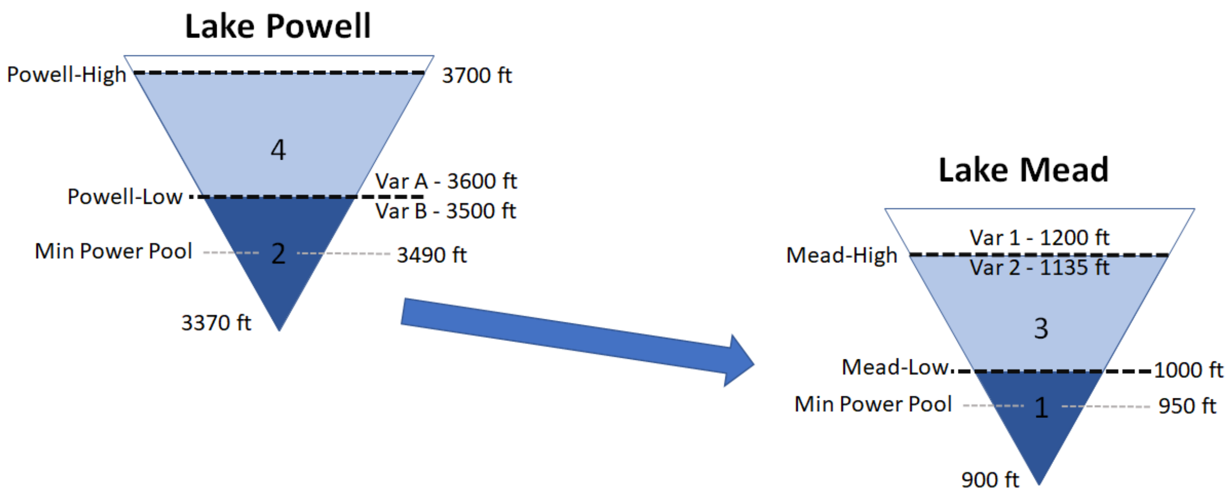

Figure 9.7. Conceptual schematic of the strategy for implementing Fill Mead First – Phase One.

We evaluated the four combinations of variation A and B for Lake Powell and variation 1 and 2 for Lake Mead, providing a sensitivity analysis of how these variables affect water supply reliability. The four combinations are considered as alternatives and hereafter, we refer to these combinations as FMF-1A, FMF-1B, FMF-2A and FMF-2B. It should be recognized that these combinations could be considered variations of Phase Two of the original Fill Mead First proposal with greater specificity.

	Variation 1: Mead-High = 1,200 ft	Variation 2: Mead-High = 1,135 ft
Variation A: Powell-Low = 3,500 ft	Alternative FMF-A1	Alternative FMF-A2
Variation B: Powell-Low = 3,600 ft	Alternative FMF-B1	Alternative FMF-B2

Table 9.4. Alternatives under the FMF alternative management paradigm. All elevations are in feet above mean sea level (ft msl).

We also assumed that Alternative 1.A—the notion of setting Lower Basin shortages based on the combined storage contents of Lake Mead and Lake Powell—would be implemented as part of the FMF-Phase 1 alternative. In our analysis of Alternative 1.A, described in the previous section, we considered a range of shortages to the Lower Division states and Mexico in Tier 3 (Table 9.3). Here, we set the shortages in Tier 3 (Table 9.5) based on the cumulative effect of the 2007 Interim Guidelines, Lower Basin DCP, and Minutes 319 and 323 (see Table 2.1). We assumed that Upper Basin consumptive uses would continue to increase based on the UCRC (2007) Upper Basin Depletion schedules. Other shortage levels for Tier 3 and assumptions about future growth of Upper Basin consumptive uses could be analyzed.

Shortage Tier	Combined Storage Range (maf)	Arizona (maf)	Nevada (maf)	California (maf)	Mexico (maf)	Total Lower Basin Shortage (maf)
Tier 1	25.0 > Storage > 20.0	0.512	0.021	0	0.080	0.613
Tier 2	20.0 > Storage > 15.0	0.640	0.027	0.200	0.146	1.013
Tier 3	Storage < 15.0	0.720	0.030	0.350	0.275	1.375

Table 9.5. Combined storage tiers and applied Lower Basin shortages in FMF AMP (also used in FPF AMP below)

Figure 9.8 compares the operation of Lake Mead and Lake Powell based on the Interim Guidelines with the FMF-A1 alternative, using a single trace of a hydrologic scenario in which a severe dry period is followed by a wet period (i.e, a 'Dry to Wet' test hydrology). Between 2021 and 2026, the Interim Guidelines, rather than the rules of FMF-A, apply, and there is no difference in operations between the 'baseline' and the alternative. During this period, the storage contents of Lake Powell are predicted to be between approximately 3,500 and 3,650 ft msl. while Lake Mead decreases in storage from 1,090 to nearly 1,000 ft msl. Beginning in 2027, operations of the two reservoirs are predicted to significantly diverge with each other and relative to the baseline operations. In FMF-A1, storage in Lake Powell would be reduced to the top of *priority zone two* which is 3,500 ft msl throughout the assumed dry period. During these years, Lake Mead would be the main storage reservoir. In order to maintain Lake Powell at a relatively low level and route water to Lake Mead, large releases from Lake Powell would be required at the limit of the river outlets. These releases would be of a similar magnitude to those of controlled floods that now occur under the High Flow Experiment Protocol, but the duration of these floods would last for several weeks rather than several days as is presently the case. These releases from Lake Powell would be absorbed by Lake Mead and released downstream to meet Lower Basin demands. Ironically, the large releases from Lake Powell would abruptly stop if Lake Mead fills to the top of *priority zone three*. Thereafter, water storage would occur in Lake Powell in *priority zone four* and Lake Powell's releases would be similar to today's operating strategy. Despite the very different operating strategy of this alternative, the modelled combined storage of the two reservoirs is almost identical to the baseline strategy (Figure 9.8.C).

Figure 9.8. Reservoir characteristics comparing baseline and the FMF-A1 AMP with a sample Dry to Wet hydrology. (A) shows Lake Powell elevations, inflows, and outflows. (B) shows Lake Mead elevations, inflows, and outflows. (C) shows combined storages with shortage thresholds.

We also evaluated the implications of the FMF-B2 alternative using the same 'Dry to Wet' hydrologic single trace that we consider above. The FMF-B2 alternative allows a narrower operational space for Lake Mead and assumes larger storage in Lake Powell by using different elevation ranges for *priority zones three* and *four*. The objectives of this alternative are to maintain Pearce Ferry Rapids as a fragmentation barrier separating the fish communities in Lake Mead from those in the river through the Grand Canyon and to maintain a higher hydraulic head in Lake Powell. During the dry period in the early part of this 'Dry to Wet' test hydrologic scenario, Lake Mead would be drained to its minimum level of 1,000 ft msl as more water is stored in Lake Powell. Nevertheless, water storage in Lake Powell is less than the defined Powell-Low elevation for much of the first half of the modeling period (Figure 9.9). Releases from Lake Powell would vary considerably in this case, with more variable releases that include some months of large releases whenever Lake Powell reaches the Powell-Low elevation, and releases similar to the modern flow regime in other years. During the onset of the wet period in the latter part of the hydrologic scenario, *priority zone three* is filled sooner because of the lower elevation limit imposed to maintain Pearce Ferry Rapid.

Figure 9.9. Reservoir characteristics comparing baseline and the FMF-B2 AMP with a sample Dry to Wet hydrology. (A) shows Lake Powell elevations, inflows, and outflows. (B) shows Lake Mead elevations, inflows, and outflows. (C) shows combined storages with shortage thresholds.

This analysis demonstrates that the flow of the Colorado River in the Grand Canyon would be very different in different portions of the modeled period with the monthly flow regime of some years being similar to the natural regime, subject only to the hydraulic limitations of the penstocks and river outlets at Glen Canyon Dam. Other periods modeled in this hydrologic scenario, however, are predicted to have flow patterns driven only by the timing of Lower Basin demands, and potentially by regional demands for electricity as is the case today. Thus, the modeling suggests that there would be two very different flow regimes in the Grand Canyon. The threshold between these two flow regimes would occur when the reservoirs reach the fixed operational target levels of *priority zones three* and *four*. Shifts in the flow regime from one inter-annual pattern to another is likely to be highly disruptive to the existing novel ecosystem and potentially to the recreational river boating economy. Also, the sustained large releases from Lake Powell would exacerbate existing sediment deficit conditions and cause widespread erosion of sand bars unless the sand supply was augmented from the delta deposits of Lake Powell. There are some strategies that might be implemented to mitigate some adverse impacts of the FMF alternative. For example, a 'buffer' volume could be established in Lake Mead whenever *priority zone three* might be drained or exceeded, thereby allowing Lake Powell to make releases in patterns that are more conducive to desired flows in the Grand Canyon.

The FMF alternative does not significantly improve reservoir storage and water delivery to the Lower Basin during severe sustained drought. We analyzed performance of the four FMF alternatives under the stress of the Millennium Drought (2000 Resample) and the Paleo Tree Ring Drought (1576 Resample) and compared that performance to reservoir conditions during the very wet DNF hydrology (Figure 9.10). Although there is a small amount of increased storage during either of the drought scenarios, the steep downward decline in reservoir storage is not arrested. We conclude that **the impact of increasing Upper Basin consumptive uses as forecast by the 2007 UCRC future depletion schedule has a greater effect on decreasing reservoir storage contents than the small savings in evaporative losses resulting from the reoperation of lakes Mead and Powell.** Protecting Pearce Rapid from being inundated by reducing the storage space available in Lake Mead (FMF-B1 versus FMF-B2) has an effect on reservoir operations only during wet conditions, which is included in the DNF hydrology scenario. In the dry conditions of the Millennium Drought (2000 Resample) and the Paleo Tree Ring Drought (1576 Resample), the Pearce Ferry Rapid would remain exposed regardless of the alternative used.

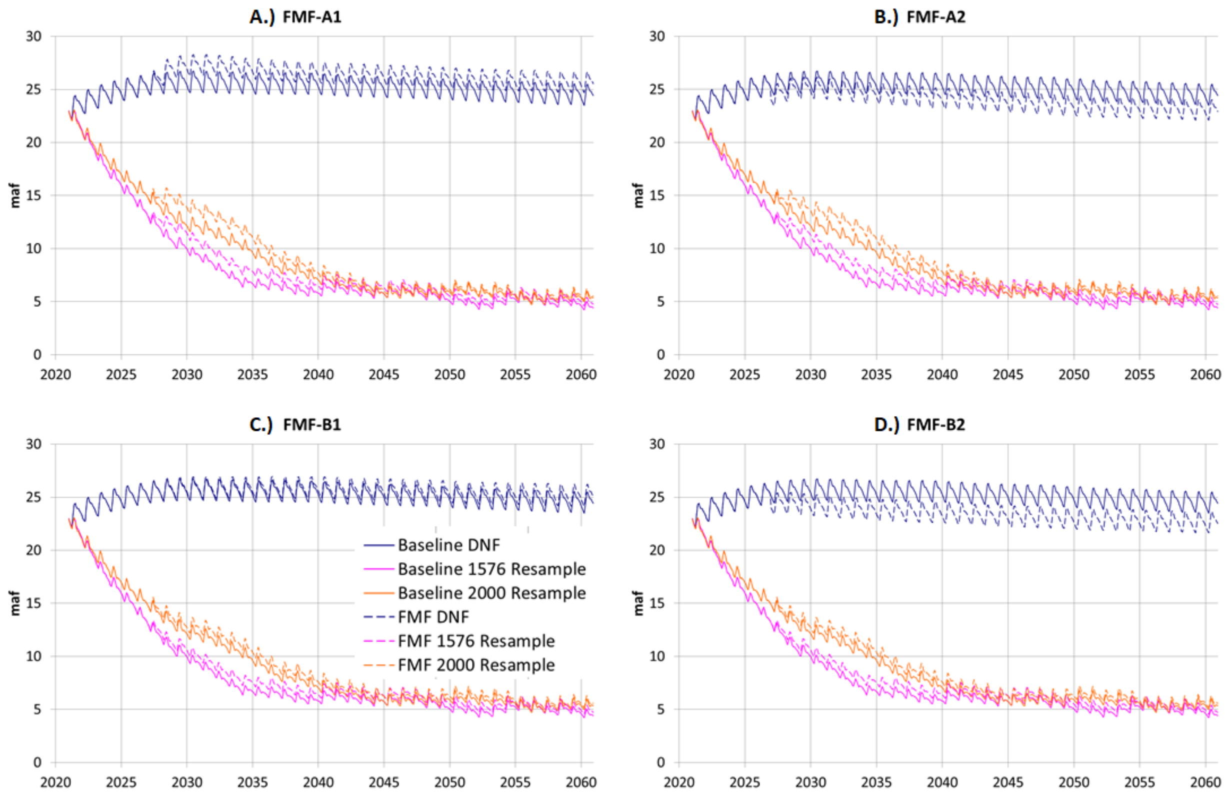

Figure 9.10. Combined storage under FMF Management Alternatives when using the Millenium Drought (*2000 Resample*), Paleo Tree Ring Drought (*1576 Resample*), and DNF hydrology.

To further understand the implications of the FMF policy, the average shortages to Lower Basin and Mexico water users are shown in Figure 9.11. As the policies begin, all FMF Management Alternatives show an initial increase in shortages, but these differences diminish over three to eight years if the droughts persist, again indicating that the proactive reductions assumed in this policy are not sufficient to reduce the risks of an enduring drought.

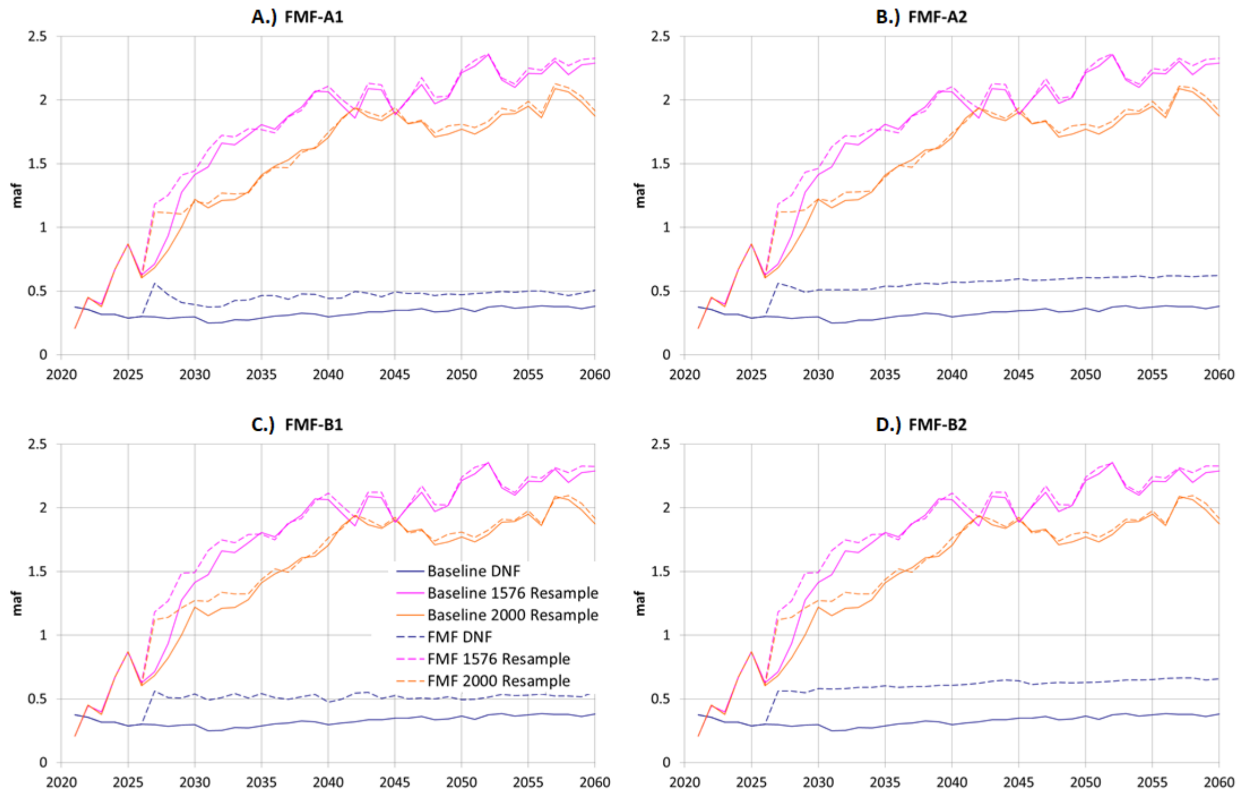

Figure 9.11. Average Lower Basin + Mexico Shortages under FMF Management Alternatives when using the Millenium Drought (*2000 Resample*), Paleo Tree Ring Drought (*1576 Resample*), and DNF hydrology.

There is little difference in the combined water storage or the shortages to Lower Basin water users under any of the variations of the FMF alternative management policy. In other words, **from a water supply perspective, the choice of which reservoir the water is stored in and released from has little effect on water supply availability for the Lower Basin States and Mexico.**

Although a FMF policy would have little effect on water supply, this policy would alter flows through the Grand Canyon. The impact of a FMF policy on flow regime at Lees Ferry using the Millennium Drought, Paleo Tree Ring Drought, and DNF future hydrologic scenarios are shown in Figure 9.12 in terms of the Alteration Index (Section 8). In all scenarios, spring to early summer runoff flows frequently remain much lower than historic (pre-dam) flows and similar to current post-dam flows (Figure 9.8.A and 9.9.A). Most variation in the Alteration Index across hydrologic scenarios and FMF policies occurs in the winter. In current post-dam conditions, flows are higher in the winter relative to pre-dam flows (i.e. dots greater than 1 in winter months). In several combinations of the hydrologic scenario used and FMF management alternatives, high, low, and median flows are lower and more similar to pre-dam conditions (i.e. colored bands closer to 1 during winter months). This is especially apparent when considering the Paleo Tree Ring and Millennium Drought hydrologic scenarios. Despite flows in the winter appearing more natural under these future scenarios, the frequently constrained flows (of all magnitudes) during the runoff season would likely prevent any ecological benefits of these scenarios because these runoff flows during the spring and early summer months are important for most ecological processes (e.g. fish reproduction). Because the alteration index is developed using all points in time, it represents long-term average conditions and does not capture the binary nature of the implications of the FMF policy for the Grand Canyon as demonstrated in the single-trance analyses shown in Figure 9.8 and Figure 9.9. It does however provide a useful metric to understand the degree of engineering manipulation and improvement that these policies can provide.

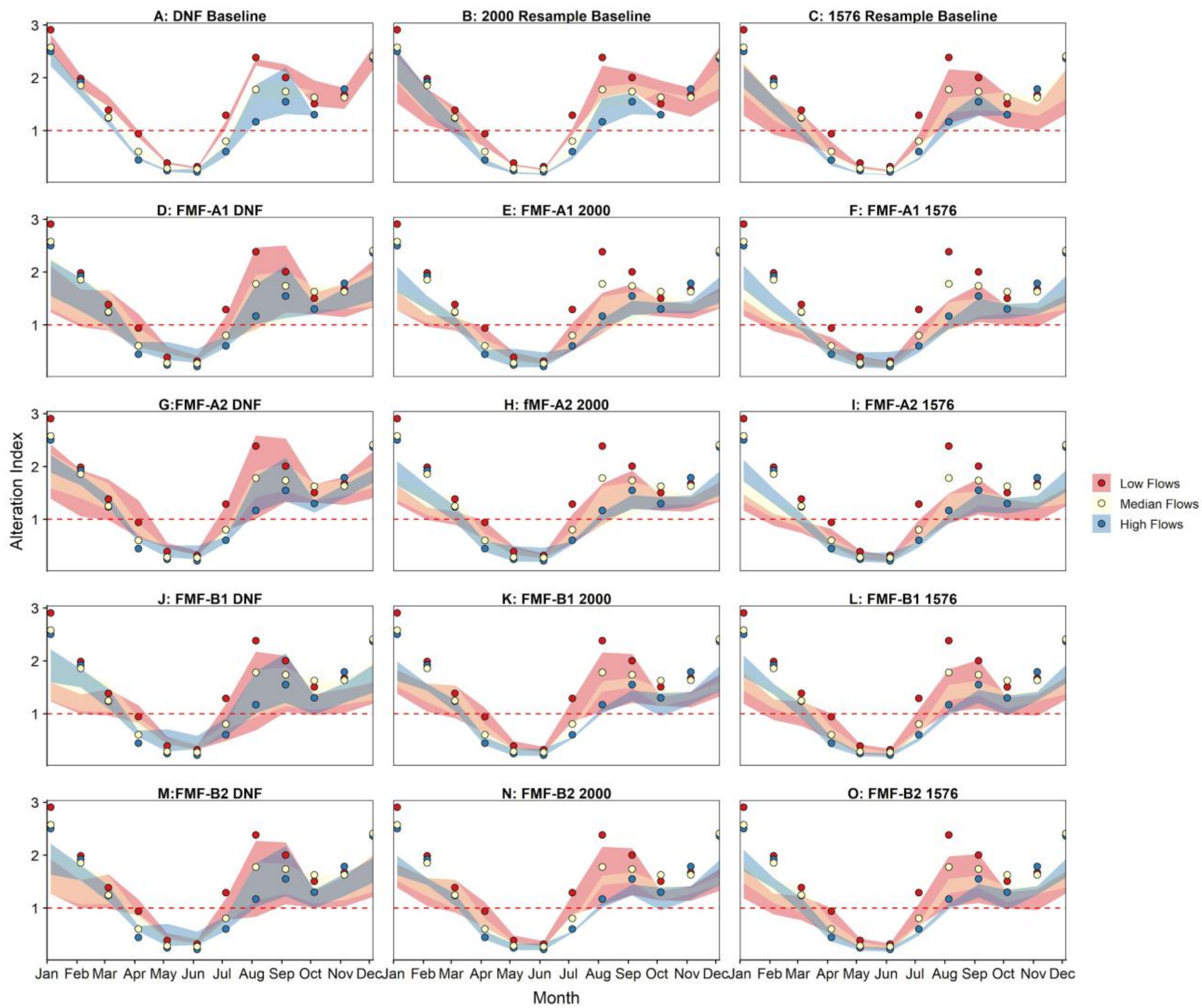

Figure 9.12. The Alteration Index was calculated to compare 25th (low flows, red), median (yellow), and 75th (high flows, blue) percentiles of future flows (calculated across the entire period) predicted for the different versions of the Fill Mead First alternative to historic, pre-dam flows. The shaded ribbons represent variation in the Alteration Index across runs, while the points represent the Alteration Index calculated for the modern, post-dam period (1990-2015) to

compare future monthly flow alteration to current alteration. The red dashed line at 1 represents flows that are most similar to pre-dam conditions.

9.3 Evaluation of Alternative II.B: Fill Powell First (FPF)

The FPF alternative would prioritize storage in Lake Powell and use Lake Mead as a secondary facility. This alternative is the antithesis of the FMF alternative and has not been formally proposed by any organization or agency. The present operations derived from the 2007 Guidelines often attempt to equalize the volume of stored water in the two reservoirs. When the annual release from Lake Powell is required to fall between limits according to the 2007 Interim Guidelines, equalization is referred to as 'balancing' the storage. An equalization policy is an intermediary between the two 'bookend' alternative policies of FMF and FPF. Comparison of these alternative management policies with the current operations sheds further light on whether there are ways to minimize system losses, improve water supply security, and increase the flexibility of releases from Lake Powell to allow more adaptive management of ecosystem rehabilitation in the Powell-Grand Canyon-Mead system.

The primary objectives of the FPF strategy would be to:

- reduce system-wide evaporation losses by consolidating water storage in one facility;
- maintain more water above both dams structures to allow flexible power generation;
- maintain fragmentation between Lake Mead and the western Grand Canyon, potentially limiting movement of non-native fish species into western Grand Canyon.

Similar to our analysis of the FMF alternative, there are many nuances in the implementation of the FPF alternative. These issues concern the need to protect critically low elevations in each reservoir, how full Lake Powell should be before water storage begins in Lake Mead, and concerns associated with flood control operations at the two reservoirs.

Even though the emphasis of the FPF alternative is storing water in Lake Powell, we assumed that maintaining a sufficiently high pool elevation of Lake Mead to protect the intakes for the Southern Nevada Water Authority would still be a primary objective. We therefore assumed that *priority zone one* would be the volume in Lake Mead below the Mead-Low elevation of 1000 ft msl. Thus, if only a small amount of water is available to be stored, it would be preferentially stored in this zone (Figure 9.13). Once *priority zone one* is filled, additional water beyond what is required to meet downstream delivery requirements in the Lower Basin would be stored in Lake Powell up to its maximum capacity of Powell-High; we defined these zones as *priority zones two* and *three*. Additional water would be stored in Lake Mead only after *priority zone three* in Lake Powell had been filled; thereafter, water would be stored in Lake Mead in *priority zone four* up to the elevation of Mead-High. Similar to the FMF alternative, if the elevation of Lake Powell nears its maximum allowable elevation, current operations to avoid uncontrolled spills and the use of the emergency spillways would thereafter govern operations of Glen Canyon Dam. Dam safety would need to be a significant operational consideration in the FPF alternative.

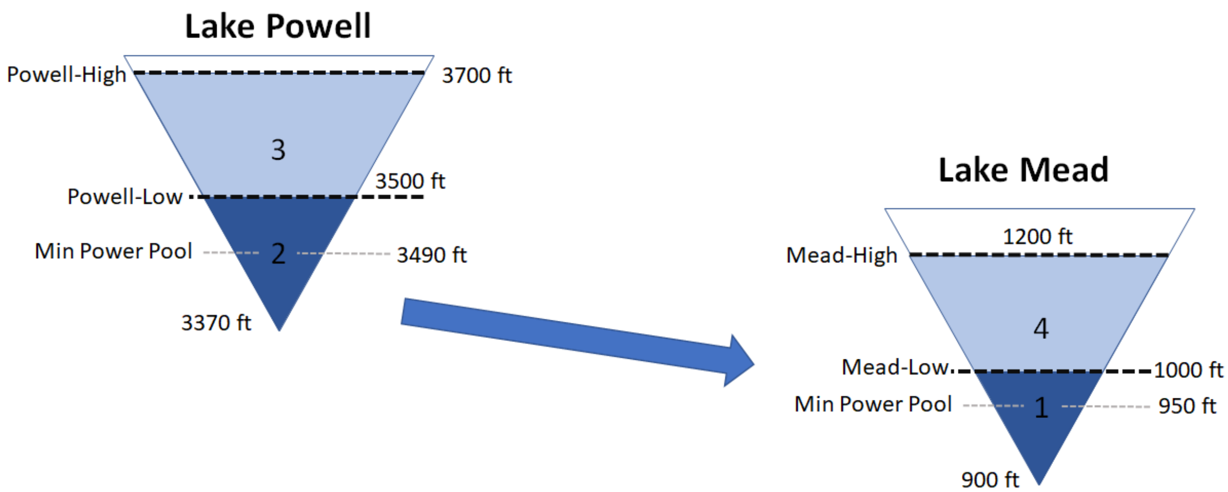

Figure 9.13. Conceptual schematic of Fill Powell First AMP

Model runs analyzing the FPF plan applied many of the same assumptions used in analysis of the FMF plan. These assumptions included:

- The definitions of shortages in the Lower Basin were based on the combined storage of Lake Mead and Lake Powell. Those shortage assumptions are identical to those used in the FMF analysis (Table 9.5);
- Upper Basin consumptive uses increase in the future as predicted by the UCRC (2007) future depletion schedule;
- the Interim Guidelines and DCP rules remain in force until 2026.

We illustrated the implementation of the FPF plan by comparing the management of Lake Mead and Lake Powell using this alternative with the current reservoir operations and using the same single trace hydrologic scenario applied in Figures 9.8 and 9.9 (Figure 9.14). This hydrologic scenario includes a period of low flow years followed by a period of high flow (i.e, a 'Dry to Wet' test hydrology). Examination of this figure shows that after the 2007 Interim Guidelines expire in 2026 and the FPF policy is initiated, water storage in Lake Mead quickly decreases to its minimum level (*priority zone one* at Mead-Low elevation). Thereafter, Lake Mead storage remains at this minimum level throughout the drought period. During this period, Lake Powell re-regulates all the incoming flow from the Upper Basin, and Lower Basin demands are met by releases from Lake Powell along with any intervening inflows. Lake Mead would be operated as a run-of-river facility during this period. Shortly after the wet period begins, Lake Powell fills to the maximum level defined by the Powell-High elevation. Additional water can then be delivered to and stored in Lake Mead. During this period, high flows would occur through the Grand Canyon during the months of natural seasonal Upper Basin runoff. In some of the years of this scenario, exceptionally large releases are required from Lake Powell to avoid overtopping the dam. Even under the current operations (i.e. the baseline operations defined by Reclamation), CRSS projects that monthly releases of 59,000 ft^3/s would occur in some years, and as framed in this study, the maximum monthly release would be 64,000 ft^3/s using the FPF alternative.

Both the baseline and the FPF alternative would require use of the Glen Canyon Dam spillway in this hydrologic scenario.

Figure 9.14. Reservoir characteristics comparing baseline and the FPF policy with a sample 'Dry to Wet' test hydrology. (A) shows Lake Powell elevations, inflows, and outflows. (B) shows Lake Mead elevations, inflows, and outflows. (C) shows combined storages with shortage thresholds.

Because the FMF and FPF policies represent two extreme 'bookends' of reservoir operations, we compared their performance in terms of three elements of water-supply mass balance: combined reservoir storage, the combined reservoir evaporation, and the total shortages to the Lower Basin and Mexico (Figure 9.15). This comparative analysis demonstrates the relatively small effect that a significant reoperation of the two reservoirs has on the overall mass-balance of the system. The small increase in storage (A) and resulting increases in evaporation volumes (B) under either of the FMF or FPF policies is largely driven by the selected shortage policies chosen in Table 9.5, which is noted in (C). In other words, the evaporation savings that was perceived to occur with either of these two policies is overshadowed by the specific choice of shortage policy that is selected.

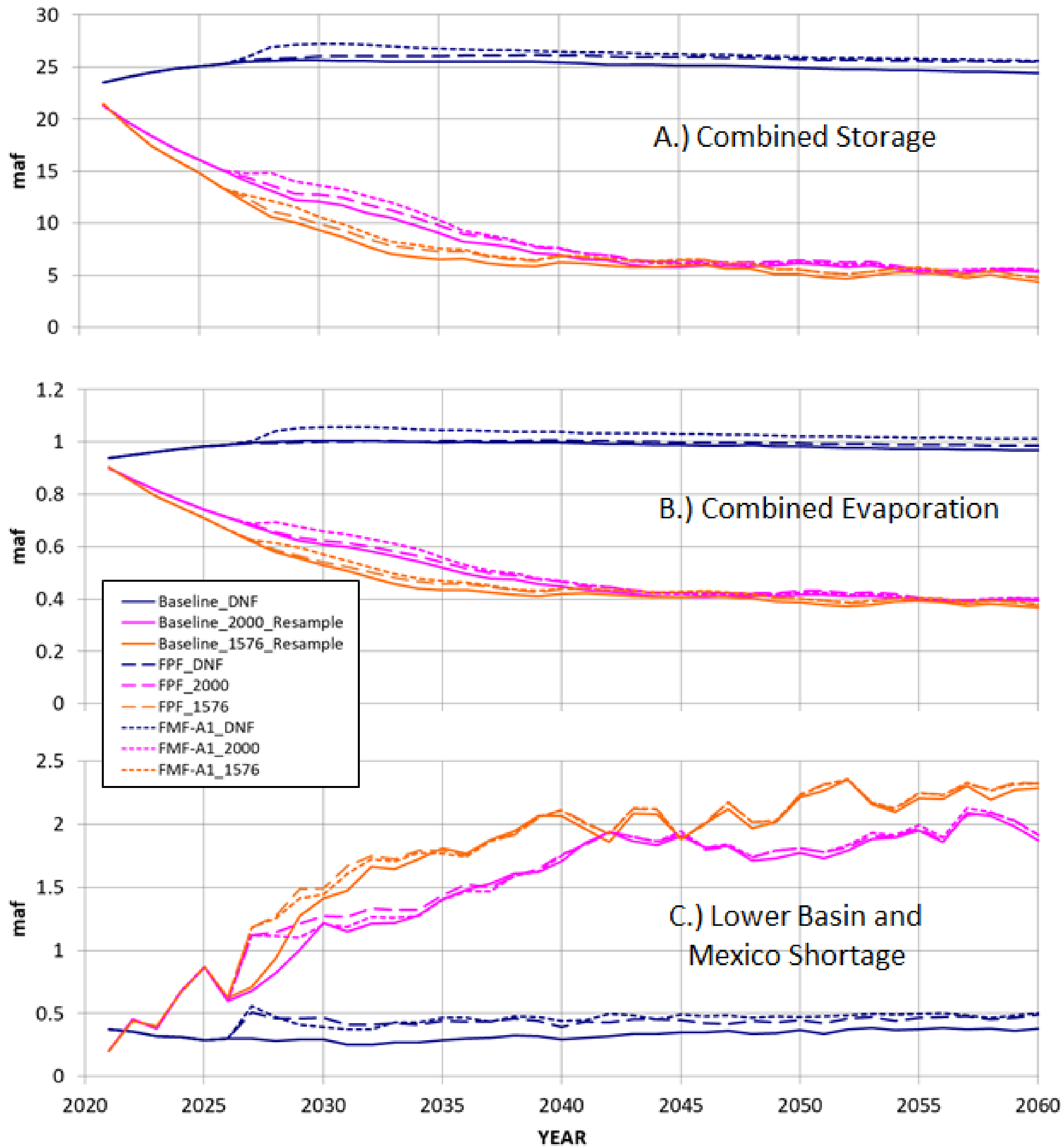

Figure 9.15. Comparison of FMF-1A and FPF Management Alternatives when using average values from hydrologic traces of the Millennium Drought (2000 Resample), Paleo Tree Ring Drought (1576 Resample), and DNF hydrology. (A) shows combined storage of Lake Mead and Lake Powell; (B) shows combined evaporation from Lake Mead and Lake Powell. (C) shows total Lower Basin and Mexico shortages.

Although there is little difference in the performance of the aggregated Powell-Mead system under either the FMF or FPF alternative, the very different rules that would control the releases from the reservoirs under these management plans would cause significant differences in the duration of time that each reservoir remains at critically low levels, thus resulting in significantly different temperatures of the flows that would pass through the Grand Canyon. The differences in the predicted duration of time that the pool level of Lake Powell falls below each elevation are shown in Figure 9.16, based on model runs that use all traces in the DNF, Millennium Drought (2000 Resample), and Paleo Tree Ring Drought (1576 Resample) hydrologic scenarios. The maximum continuous duration is the worst-case scenario (i.e. longest duration) and percentiles show the density distributions of the longest periods below the thresholds (the longest 25% of all such periods).

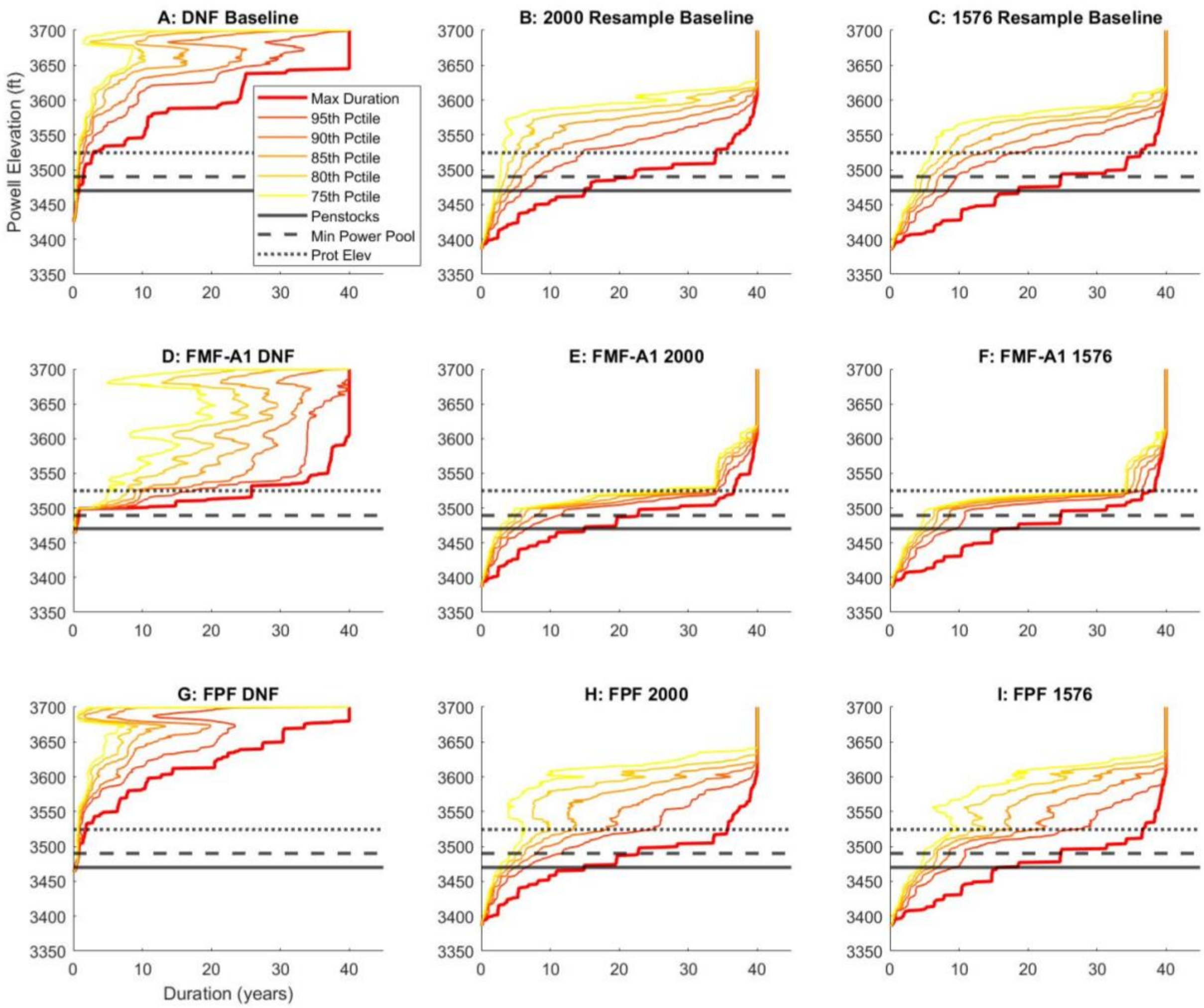

Figure 9.16. Duration of instances that Lake Powell falls below pool elevations when using the DNF (A, D, G), Millennium Drought (2000 Resample; B, E, H) and Paleo Tree Ring Drought (1576 Resample; C, F, I) hydrologic scenarios. Reservoir operations considered are Baseline (A, B, C), FMF-A1 (D, E, F), and FPF (G, H, I).

Under current operations and the future depletion schedules projected by the UCRC (2007), if the Millennium Drought persisted (panel B) or the Paleo Tree Ring Drought returned (panel C), the elevation of Lake Powell would be lower than Minimum Power Pool for prolonged periods of 20-25 years. Emphasis on using Lake Mead as the primary storage reservoir, which is the goal of the FMF policy, necessarily increases the duration of time that Lake Powell would be low levels (panels E and F). The FPF policy would reduce the frequency of the low Powell conditions, but would not eliminate the risk of low Powell conditions during extended droughts (panels H and I). One notable result observable in Figure 9.16 is the relatively little change of the maximum duration droughts among the baseline, FMF, and FPF policies, particularly under the drought conditions (2000 Resample and 1576 Resample). Our model results suggest the contents of Lakes Powell and Lake Mead would be fully depleted during the worst drought conditions reflected in the hydrologic scenarios, and operational changes of implementing FPF or FMF cannot avert that dire situation. On the other hand, implementation of FPF or FMF would not exacerbate these worst-case scenarios.

Although the Lower Basin water supplies issues are not significantly changed by FPF or FMF, these two policies would result in very different flow regimes in the Grand Canyon, as demonstrated in the single trace examples in Figures 9.8, 9.9 and 9.14. Figure 9.17 shows the Alteration Index, demonstrating the degree to which the policies that change flow regime are more or less similar to natural conditions.

During severe droughts, the summer and fall flow regime of the Colorado River through Grand Canyon is more similar to natural conditions if the FMF policy is adopted; the Alteration Index is closer to 1 during the months of July through October relative to contemporary post-dam flows (Fig. 9.17). However, as discussed in the FMF section, these more natural flows are unlikely to be beneficial to ecosystems if the annual spring snowmelt flood is not restored—i.e. spring and early summer flows remain low and the Alteration Index remains significantly less than 1. Similarly, the FPF policy retains highly altered flows in the spring and summer months, but retains the unnaturally high late season flows similar to contemporary conditions. As identified in Figures 9.8, 9.9, and 9.14, however, the implications of these policies on Grand Canyon flows are substantially different based on what the current storage levels are in each of the reservoirs, and whether Lake Powell is acting as a run-of-river reservoir, or is being operated to meet Lower Basin demands while Lake Mead is acting as a run-of-river reservoir. Comparisons of the FMF and FPF policies suggest that changes to monthly operations (see Grand Canyon Engineered Flood Flows) are more likely to influence the Alteration Index relative to these longer-term storage alternatives.

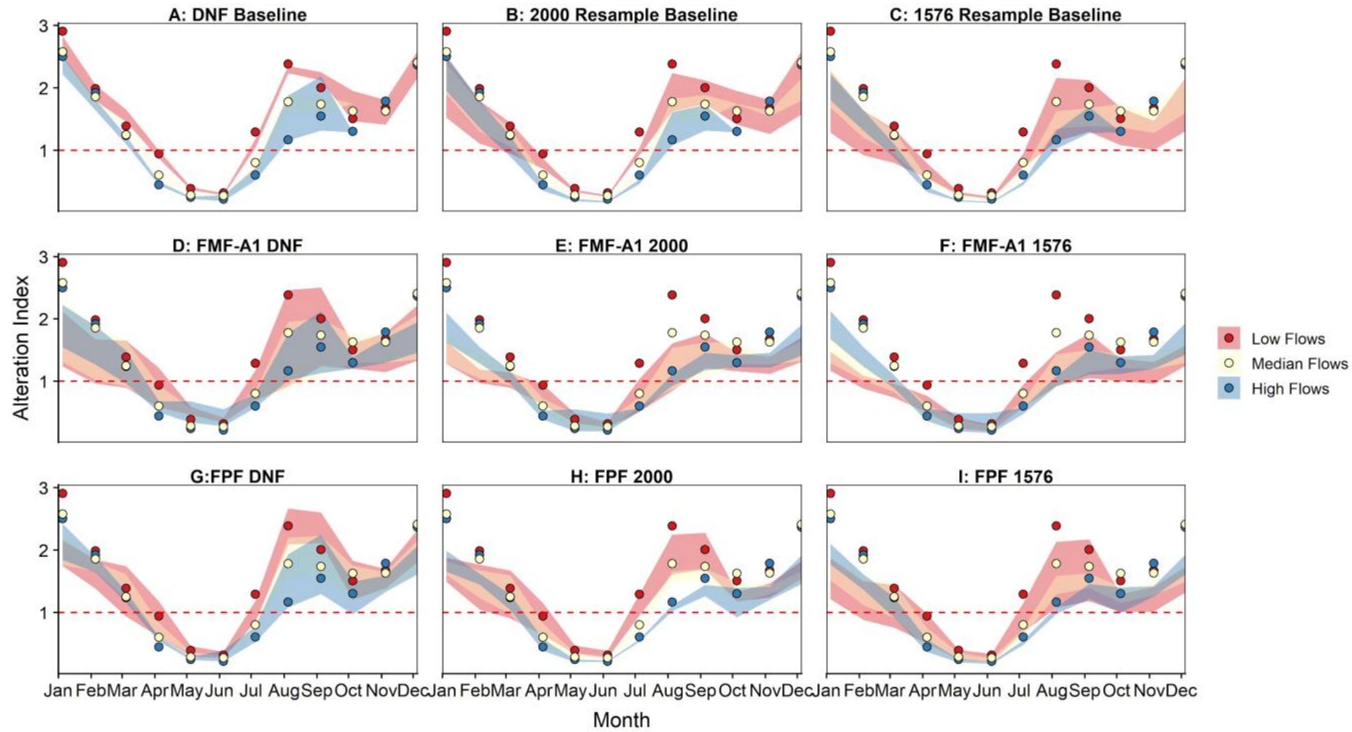

Figure 9.17. The Alteration Index was calculated to compare 25th (low flows, red), median (yellow), and 75th (high flows, blue) percentiles of future flows (calculated across the entire period) predicted for the different versions of the Fill Powell First alternative to historic, pre-dam flows. The shaded ribbons represent variation in the Alteration Index across runs, while the points represent the Alteration Index calculated for the modern, post-dam period (1990-2015) to compare future monthly flow alteration to current alteration.

The implications of these policies on the ecosystems within the Grand Canyon are driven by the releases from Glen Canyon Dam and the temperature regimes in the Colorado River, which are predominantly determined by the pool elevation of Lake Powell. Low pool elevations in Lake Powell result in warmer releases into the Grand Canyon, and the longer this pool elevation remains low, the more thermal energy is discharged into the Grand Canyon ecosystem.

The implications on the summer release temperatures from the Glen Canyon Dam are shown in Figure 9.18 for the Baseline operations, FMF and FPF AMPs, using the DNF, 2000 Resample and 1576 Resample hydrologic scenarios. The X axes indicate the number of years (i.e. duration) that the summer temperatures are averaged over, and each line represents the distribution of traces for each duration of time. As an example, using the Baseline operations and the 2000 Resample hydrology, the summer release temperature across all traces ranged from 8 to 24°C, with a median of 18°C (Panel B, duration of 1 on the x-axis). The average summer temperatures over all consecutive 20-year periods of time ranged from 10 to 22°C, with a median at 18°C (Panel B, duration of 20 on the x-axis). This temperature is 3°C higher than the warmest reservoir release temperatures in the historical record (15°C) since Lake Powell was filled. The effect of such warm reservoir release temperatures is uncertain and dependent on factors such as resource availability and the outcome of interactions between native and non-native species. However, these warm temperatures will likely have negative effects on the trout fishery in the Grand Canyon (See Figure 9.21 and sidebar "How does water storage in Lake Powell influence release temperatures and Grand Canyon fishes?").

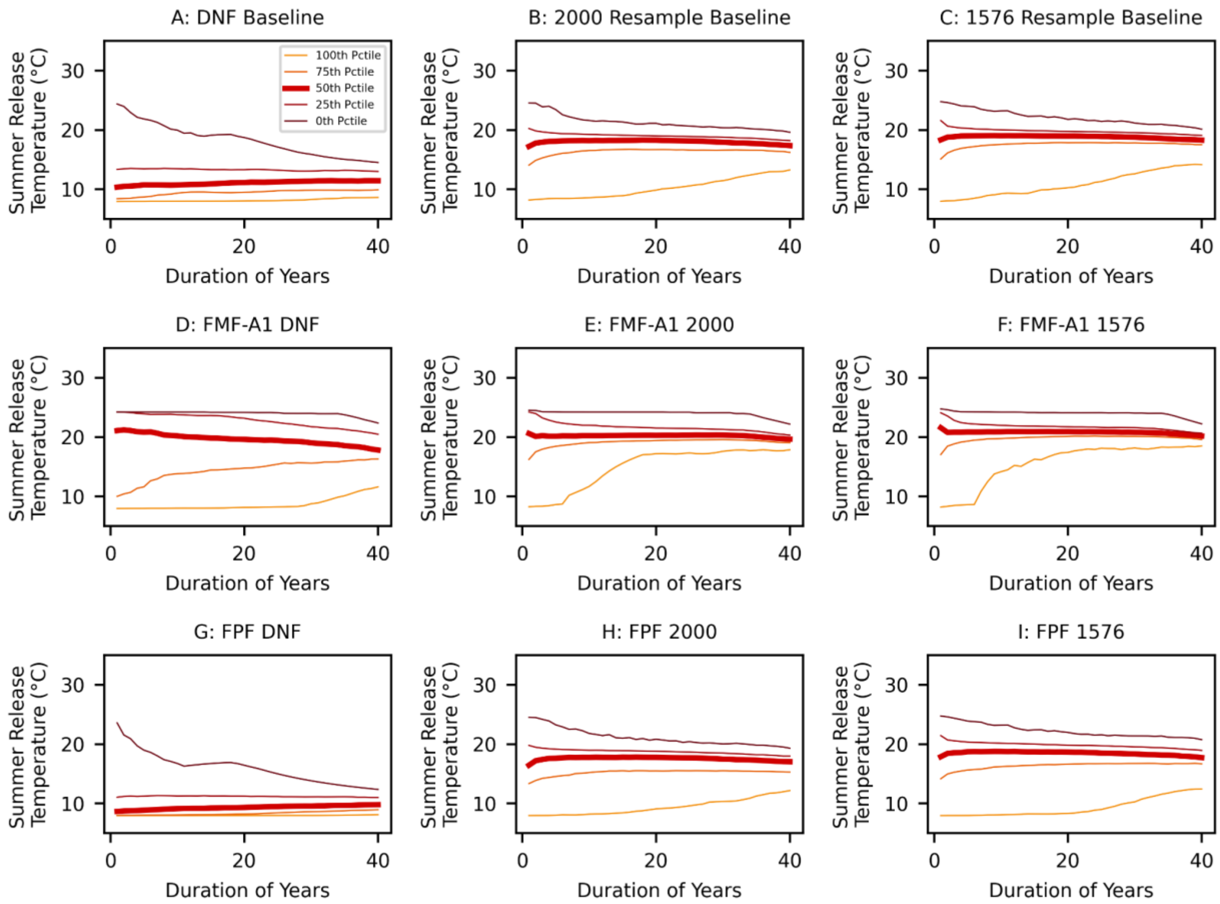

Figure 9.18. Duration of years that Glen Canyon Dam summer release temperature is above each temperature level when using the DNF (A, D, G), Millennium Drought (2000 Resample; B, E, H) and Paleo Tree Ring Drought (1576 Resample; C, F, I) hydrologic scenarios. Reservoir operations considered are Baseline (A, B, C), FMF-A1 (D, E, F), and FPF (G, H, I).

As a result of low reservoir levels in Lake Powell, the river temperature at Lees Ferry would increase well beyond recently observed values (Figure 9.19), which would cause substantial uncertainty in ecosystem outcomes. Regardless of water management policy, if hydrologic conditions are similar to either the Paleo Tree Ring or Millennium Droughts, combinations of release temperatures and discharges will likely be outside the range of post-dam conditions. Only under current management and using the DNF hydrologic scenario, which incorporates possibly unrealistic wet futures, do release temperatures stay within the range of currently observed temperatures. Summer temperatures at Lees Ferry are particularly high under the

FMF policy due to the low elevation levels in Lake Powell (Figure 9.16). Ecological outcomes of summer temperatures above 15°C are highly uncertain. While these warmer temperatures are more similar to historic, pre-dam conditions, and may be beneficial for native fish growth, reproduction, and survival, it is not known if these potential benefits will outweigh the risks associated with invasion of warm-water non-native fish from Lake Mead, which warmer temperatures would also benefit. The risk of non-native fish becoming more abundant in the Grand Canyon with warmer water temperatures is particularly concerning under the FMF policy, as there would be more available reservoir habitat beneficial to non-native fish.

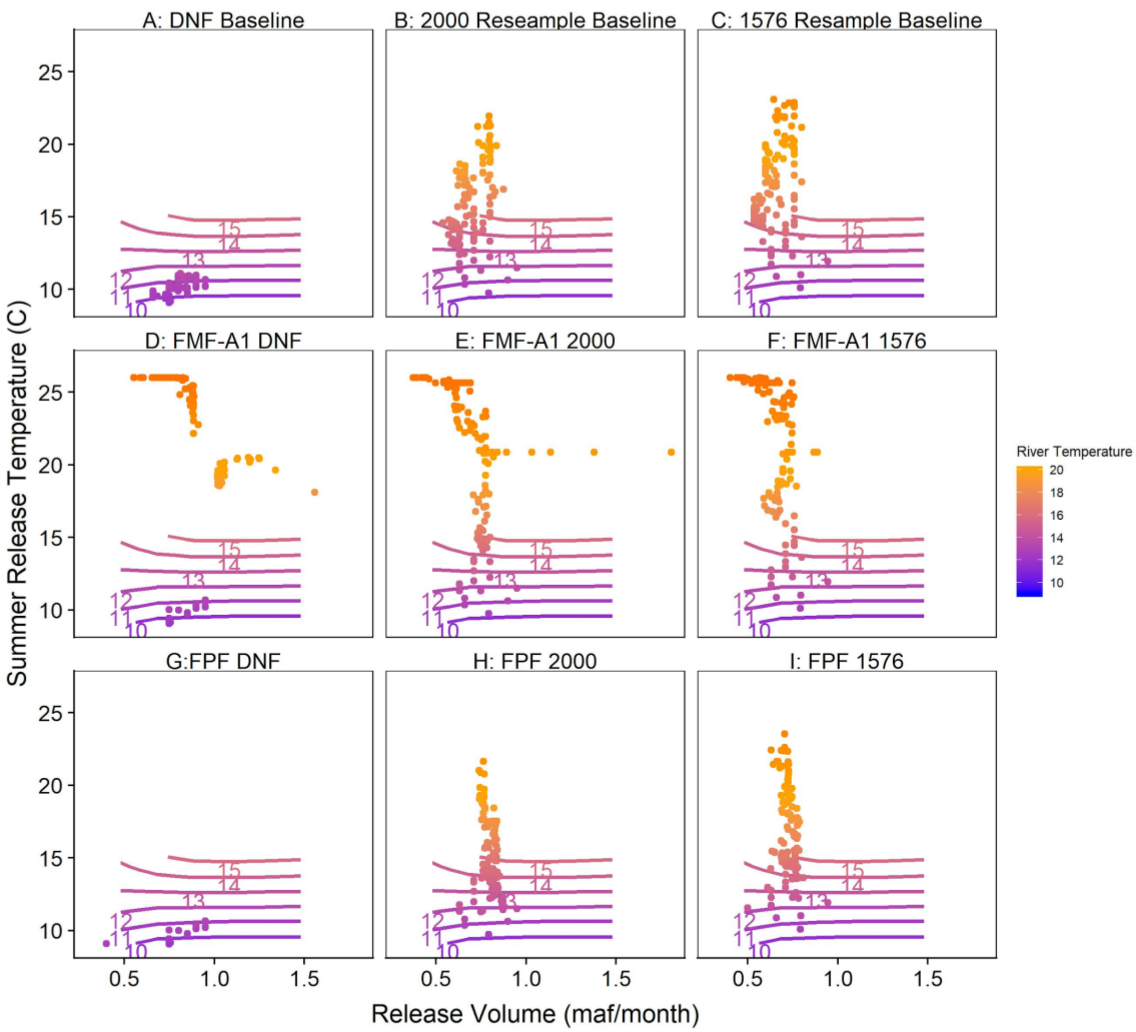

Figure 9.19. Predicted mean June, July, August, and September release volumes and temperatures summarized across runs for each year (points) relative to current ranges of Colorado River temperatures at Lees Ferry. Colors of points represent approximate predicted river temperatures, while colors of lines represent observed river temperatures for various release volume/temperature combinations.

While the effect of future release temperatures on native fishes is highly uncertain, the FMF scenario would likely lead to the collapse of the rainbow trout fishery immediately below Glen Canyon Dam. Using all three hydrologic scenarios, the probability of monthly summer temperatures being above 19°C is greater than 40%, and in several months exceeds 90% (Figure 9.20c). The probability of exceeding this threshold is similar between the Baseline and the FPF policies (Figure 9.20 a and b). These results indicate the trout fishery is likely to collapse under plausible future hydrologies regardless of whether or not water is stored in Lake Powell or Lake Mead.

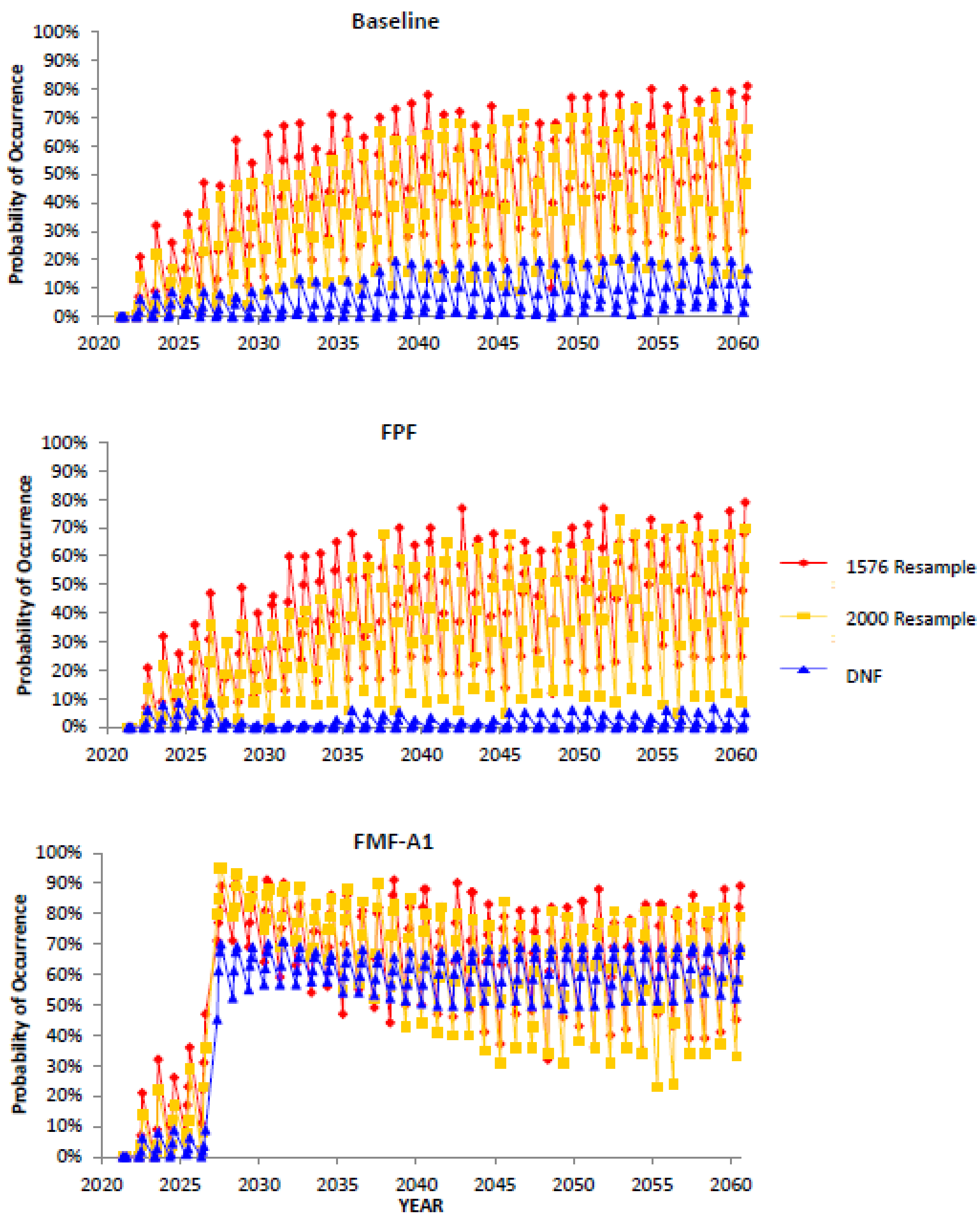

Figure 9.20. The probability that monthly mean release temperatures for June, July, August, and September are above 19°C, the upper temperature tolerance for brown trout and rainbow trout. These probabilities were calculated for the baseline operations, Fill Powell First, and Fill Mead First-A1 policies under several hydrologic conditions.

9.4 Evaluation of Alternative II.D: Grand Canyon Engineered Flood Flows

This alternative seeks to make the future monthly flow regime in the Grand Canyon similar to natural conditions to the greatest extent possible, subject other institutional and infrastructure constraints. The life history strategy of many species of native river ecosystems are cued by aspects of the natural flow regime, and implementation of this alternative might benefit those species. However, this alternative could not be implemented unless there was an associated augmentation of fine sediment, because large, clear water releases from Lake Powell would otherwise cause widespread erosion of sand bars.

Reconfiguring the distribution of monthly flows released from Lake Powell is not inconsistent with current rules for transferring water from the Upper Basin to the Lower Basin. The 2007 Interim Guidelines specify annual releases from Lake Powell based on the storage elevation of both Lakes Mead and Powell. The current guidelines prescribe releases from Lake Powell as either: 1) a specified annual volume of water, 2) an annual release of water that results in the same volume of water stored between Lake Powell and Lake Mead (referred to as 'equalization'), or 3) a 'balancing' release that is an attempt at equalization between the two reservoirs, but the annual maximum release is bound between minimum and maximum values, therefore complete equalization may not be achieved. The monthly distribution of releases, however, is primarily determined by power generation demands and are specified in Reclamation's 2016 Record of Decision for the Glen Canyon Dam Long-Term Experimental and Management Plan (LTEMP) Final Environmental Impact Statement (USBR, 2016). The LTEMP Record of Decision specifies distributions when the annual releases as specified in the 2007 Interim Guidelines is between a 7 maf/year release and a 14 maf/year. Together, the 2007 Interim Guidelines and the LTEMP Record of Decision form the basis of the assumptions used to calculate monthly flows within the CRSS. The assumptions in CRSS do not account for High Flow Experiments specified in the LTEMP.

If a minimum amount of water from Lake Powell is to be released (i.e. 7 maf), the LTEMP specifies monthly distributions that are essentially unchanging throughout the year. If the required annual release increases, higher percentages of the annual flow volume are released between January through September. In all circumstances, however, this distribution does not resemble natural flow conditions because the engineering facilities at Glen Canyon Dam limit the maximum amount of water that can be released to 45,000 ft^3/s, and Reclamation avoids using the Spillways on the Glen Canyon Dam out of safety concerns. Figure 9.21 compares the distribution for different annual release volumes with the average naturalized flow from 1906-2018 (USBR, 2020a).

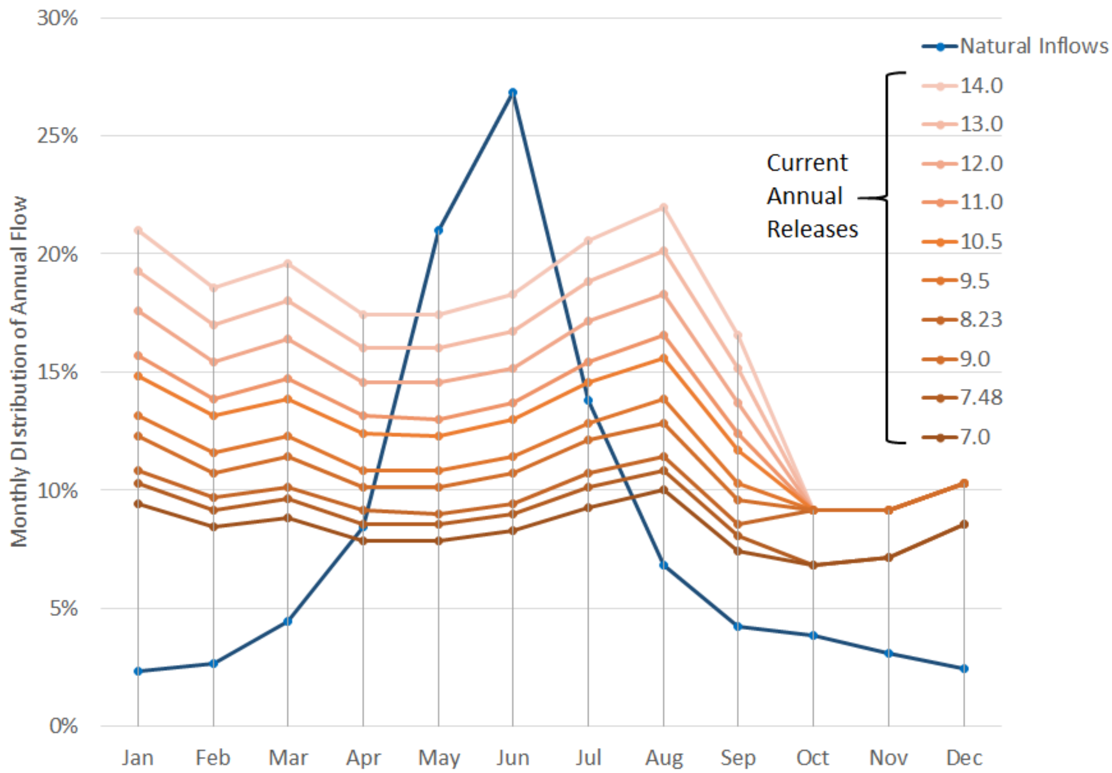

Figure 9.21. Monthly distribution of natural inflows to Lake Powell compared to monthly release distributions in CRSS under different required annual release volumes (7.0 to 14.0 maf). The area under all curves equals 100%

In this alternative, the monthly distributions of releases are modified to match the natural inflow distribution. All other operational guidelines specified in the Interim Guidelines were kept constant. Figure 9.22 shows the modeled results as monthly flow volumes, with median value of the releases (cyan) closely matching the median inflow values (red), but with substantially tighter distributions.

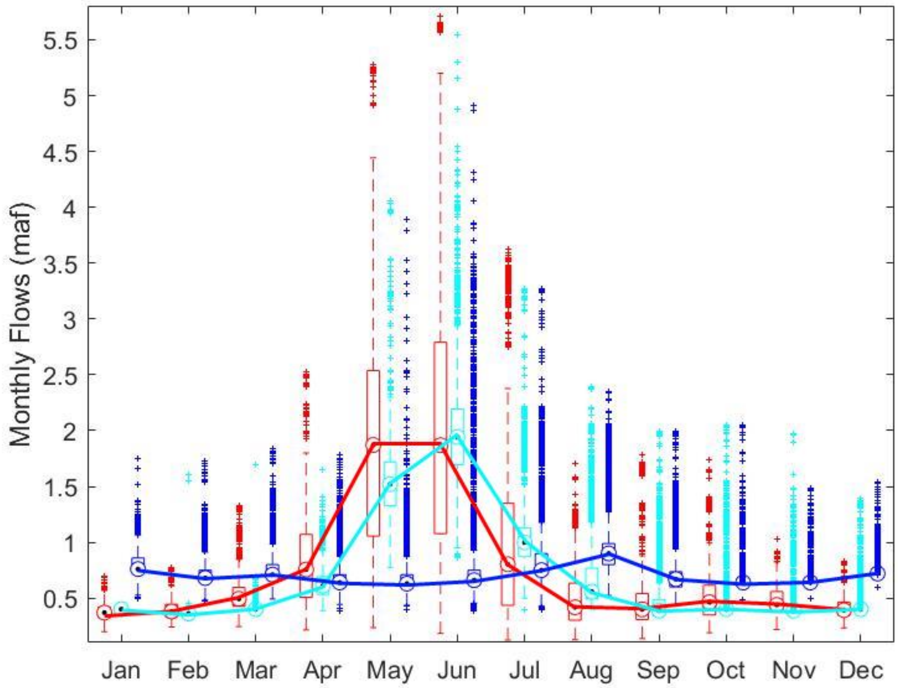

Figure 9.22 Comparison of Lake Powell inflows (red) with outflows of the Engineered Flood Flow alternative management paradigm (cyan) and outflows from current (baseline) operations (blue) using the DNF Hydrology. Median values are connected with solid lines; boxes represent 25th and 75th percentiles.

The more natural pattern of monthly flows during implementation of the Engineered Flood Flow AMP are highlighted in Figure 9.23. The Alteration Index is closer to 1 relative to contemporary post-dam conditions. This is especially apparent during the fall and winter months across all hydrologic scenarios. Late spring and early summer indices are improved using the DNF hydrology, but these improvements cannot be maintained during drought conditions. Although the Engineered Flood Flow alternative greatly improved the lower 25th percentile for flows, especially during May and June, these improvements are not as dramatic for the 75th percentile of flows. This highlights the challenge of providing high flood flows even under a management scenario aimed to provide hydrologic conditions more similar to historic, pre-dam conditions.

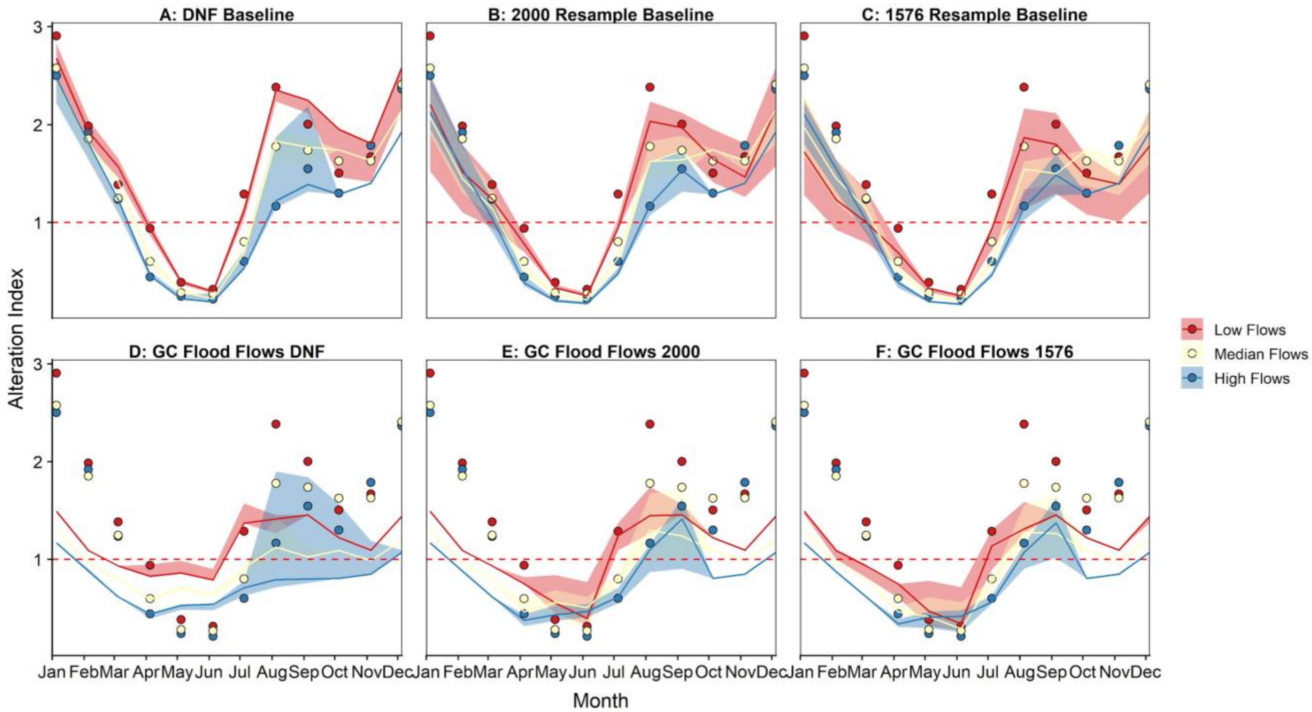

Figure 9.23. The Alteration Index was calculated to compare 25th (low flows, red), median (yellow), and 75th (high flows, blue) percentiles of future flows (calculated across the entire period) predicted for the baseline policy and the Grand Canyon Engineered Flood Flows alternative to historic, pre-dam flows for the Colorado River at Lees Ferry. The shaded ribbons represent variation in the Alteration Index across runs, while the points represent the Alteration Index calculated for the modern, post-dam period (1990-2015) to compare future monthly flow alteration to current alteration.

The implications of altering the monthly operations to a more natural flow regime are negligible to any consumptive water users, however, hydropower generation from the Glen Canyon Dam does change significantly. Not only would hydropower generation become decoupled from the current energy demand pattern, the reliable or 'firm' power generation would decrease as a result, requiring other energy sources to compensate during low flow months. Figure 9.24 demonstrates the exceedance probability of monthly energy generation under the DNF, 2000 Resample and 1576 Resample hydrology. Changing the flows to a natural regime has the inevitable result of periods of higher energy generation during seasonal flood flows and lower generation during dry seasons. In each of the hydrologic scenarios, the reliable energy generation rate is decreased. As an example, using the DNF hydrologic scenario, the 90% reliable energy generation is reduced from around 212 GWh/month to around 144 GWh/month. However, the most significant impact on power generation is the occurrence of either of the sustained drought conditions, which would cut the reliability of energy generation by more than one half.

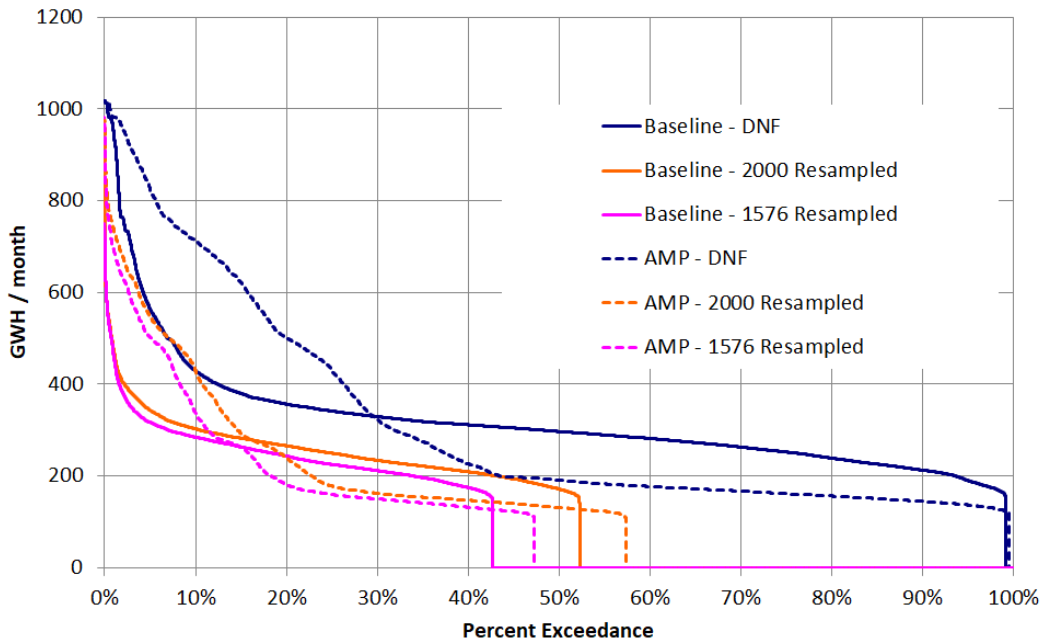

Figure 9.24. The effects of the Engineered Flood Flow alternative on monthly energy generation from Glen Canyon Dam as exceedance probabilities across DNF, Millennium Drought (2000 Resample), and Paleo Tree Ring Drought (1576 Resample) hydrologic conditions.

While our technical analysis of Grand Canyon Engineered Flood Flows has considered dam operations as determined by the 2007 Interim Guidelines, the concepts described above can be made applicable to future operations that result from the forthcoming renegotiations of these Guidelines. Once any annual release is determined, the monthly distribution could then be set based on an adaptive management process that considers several factors including the sediment supply, the temperature of the water being discharged, ecosystem implications, recreation and the need for power generation.

9.5 Evaluation of Alternative III.A: Flaming Gorge to Powell Backup

The Upper Basin Drought Contingency Plan includes an element referred to as ‘Drought Response Operations’ which specifies additional water releases from Upper Basin CRSP reservoirs (Flaming Gorge, the Aspinall Unit, and Navajo Reservoir) when Lake Powell is projected to fall below 3,525 ft msl, which is 35 ft above minimum power pool. While releases from Flaming Gorge are generally guided by the 2006 Environmental Impact Statement (USBR, 2006), the Drought Response Operation provision of the Upper Basin DCP allows additional releases from Flaming Gorge Dam by adjusting the hydrologic classifications that contribute to the determination of the annual release volumes. The Flaming Gorge to Powell Backup alternative expands and simplifies this mechanism by releasing any available stored water from the Flaming Gorge Reservoir to prevent Lake Powell from falling below an elevation of 3,600 ft msl. Figure 9.25 demonstrates how this alternative would be implemented using a ‘Dry to Wet’ sample trace during a drought condition. In this hypothetical example, Flaming Gorge storage is reduced to a minimum power pool elevation of 5,871 ft msl and held constant until Lake Powell emerges from its drought condition. Only after Lake Powell retained sufficient water would storage in Flaming Gorge begin to increase.

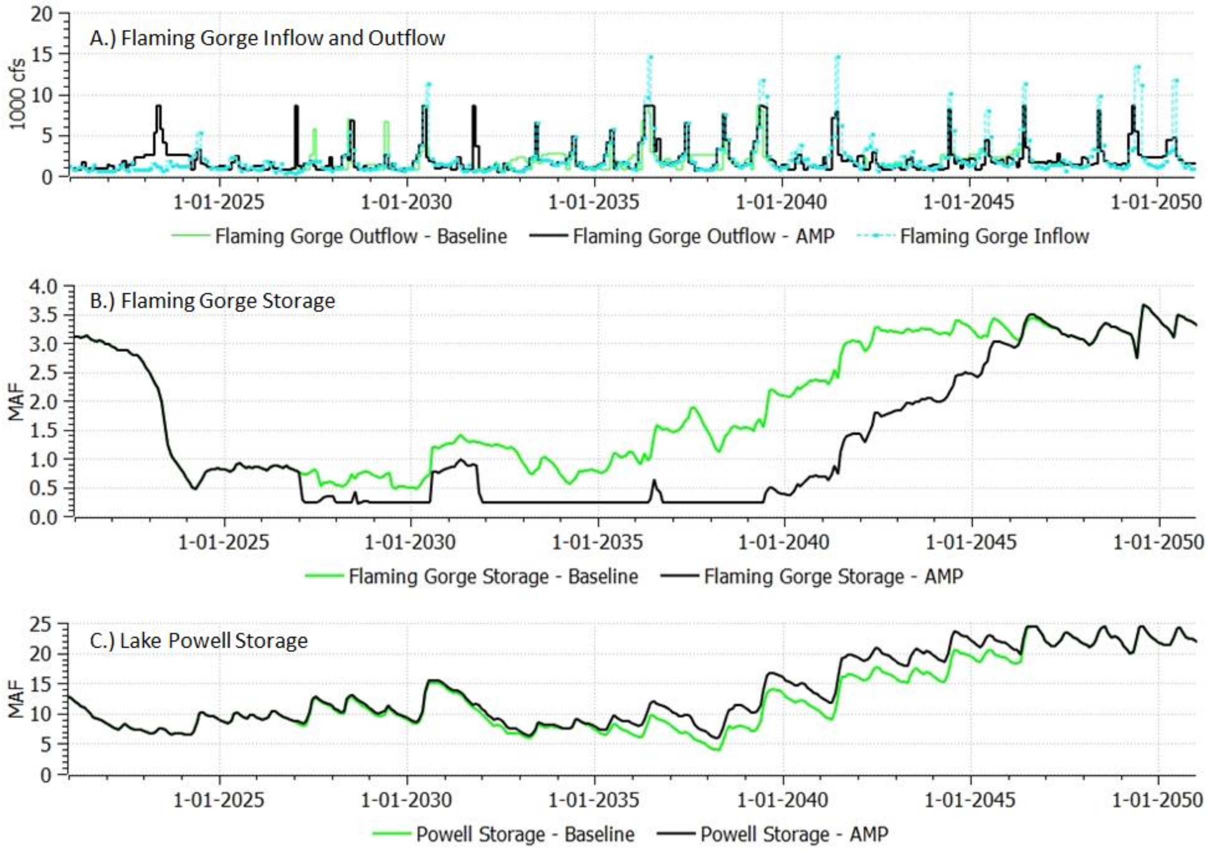

Figure 9.25. Reservoir characteristics of Flaming Gorge and Lake Powell with a backup during critical conditions. (A) shows Flaming Gorge inflows and outflows. (B) shows Flaming Gorge storage volumes. (C) shows Lake Powell storage volumes.

While there is little effect of this alternative on the flow regime during wet conditions, the flows in the Green River would change during drought conditions as the Flaming Gorge Dam would operate similar to a run-of-river reservoir. Figure 9.26 demonstrates the Alteration Index under the DNF hydrology, the *2000 Resample* hydrology, and the *1576 Resample* hydrologic conditions for both the baseline policy and Flaming Gorge backup policy. During the wet conditions of the DNF hydrology, all percentiles of flow remain above 1 (indicating wetter conditions than pre-dam hydrology) from September through January for both the baseline and Flaming Gorge backup policies. However, these fall and winter flows become more characteristic of pre-dam conditions (closer to 1) during drought conditions under the Flaming Gorge backup policy relative to drought conditions under the baseline policy (Figure 9.26 B and C) and post-dam alteration (Figure 9.26 E and F, points represent post-dam alteration). Although hydrologic conditions are more similar to pre-dam conditions in the fall and winter under the Flaming Gorge backup policy, all percentiles of flows during April through July remained lower than pre-dam conditions regardless of what policy or hydrologic scenario was considered. This is a similar result to the FMF and FPF scenarios considered for the Colorado River at Lees Ferry, in which spring and summer flows remained low regardless of the policy considered. These results highlight that changes to monthly operations in the backup plan are more likely to influence the Alteration Index during the spring and summer relative to these longer-term storage alternatives. The monthly distribution of the augmented flows routed to Powell would be important, because the timing of high flows, especially in the spring and summer, is an important cue for ecological processes such as fish reproduction.

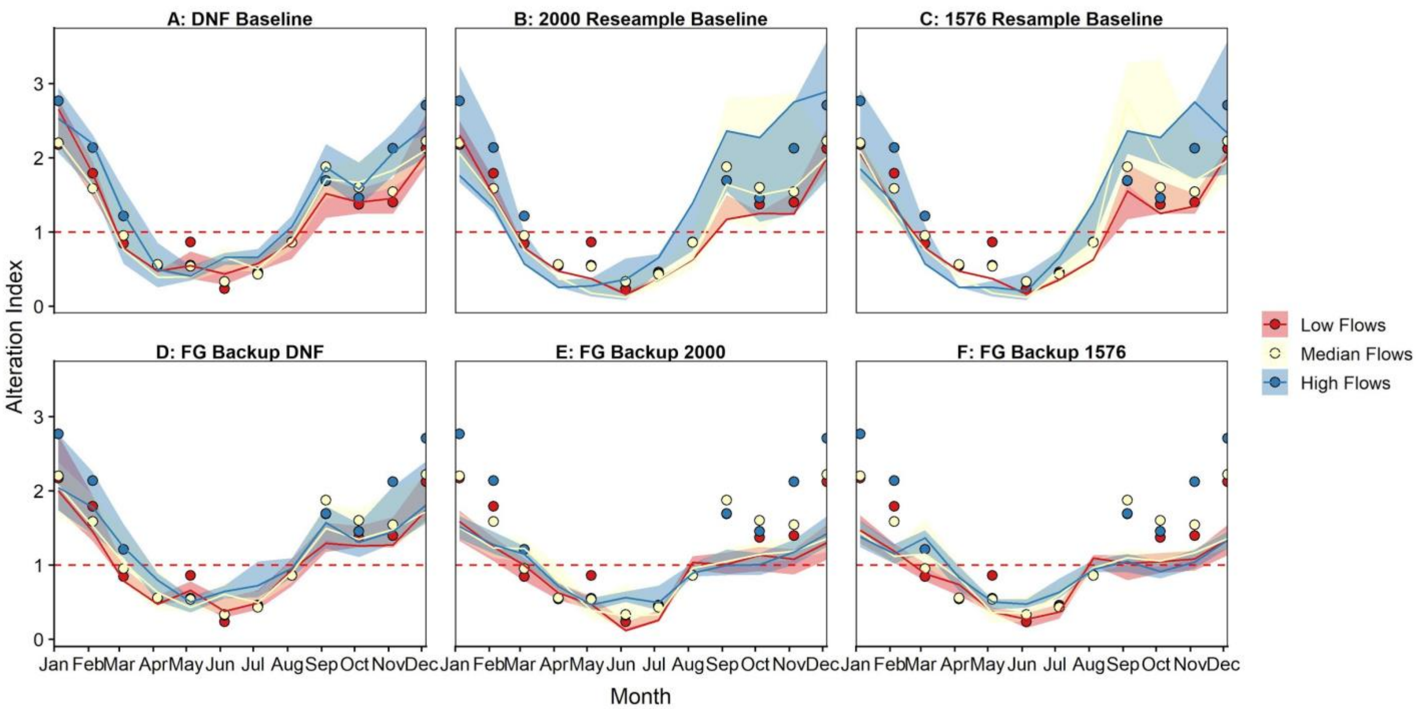

Figure 9.26. The Alteration Index was calculated to compare 25th (low flows, red), median (yellow), and 75th (high flows, blue) percentiles of future flows (calculated across the entire period) predicted for both the baseline policy and the Flaming Gorge to Powell Backup AMP to historic, pre-dam flows (1930-1960) for the Green River at Greendale. The shaded ribbons represent variation in the Alteration Index across runs, while the points represent the Alteration Index calculated for the modern, post-dam period (1990-2015) to compare future monthly flow alteration to current alteration.

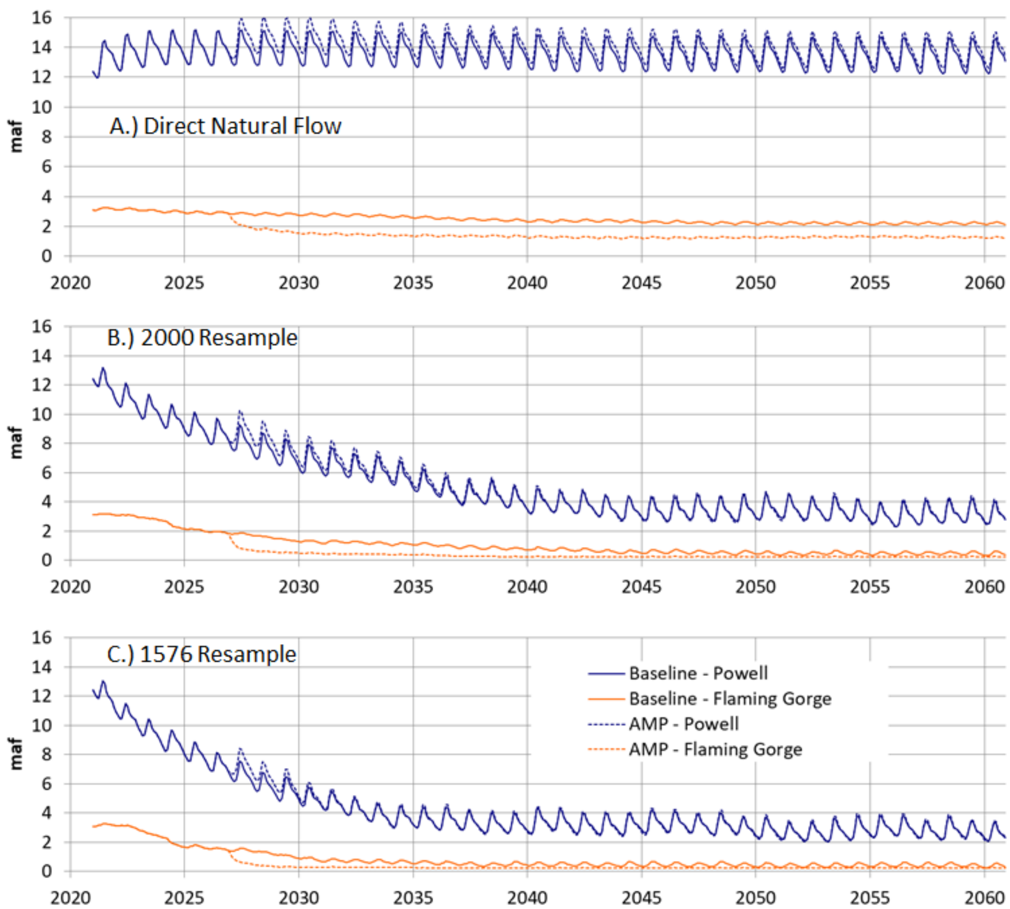

Figure 9.27. Average storage volumes of Flaming Gorge Reservoir and Lake Powell with the Flaming Gorge to Powell Backup alternative. (A) using the optimistically wet DNF hydrologic scenario. (B) using the Millennium Drought scenario (*2000 Resample*), and (C) using the Paleo Tree Ring Drought (*1576 Resample*) hydrologic conditions.

The relative storage effects on Flaming Gorge and Lake Powell are shown in Figure 9.27 across all hydrologic traces using the DNF hydrology, the *2000 Resample* hydrology, and the *1576 resample* hydrologic conditions. This shows that some, but not substantial, support for Lake Powell is provided by the Flaming Gorge Backup alternative. The average contribution of Flaming Gorge to Lake Powell across all traces is less than 1 maf, which diminishes if either of the persistent drought conditions are considered.

The minimal benefits to the Lower Basin and Mexico water users are also shown in Figure 9.28. This is expected since the Flaming Gorge reservoir empties under drought conditions, but then recaptures water during recovery periods. The minimal value of emptying the smaller CRSP reservoirs in the Upper Basin to support shortages in the Lower Basin must be weighed with and against the environmental implications that those releases might provide. As shown in Figure 9.27, ecologically important spring and summer flows would remain low, and sometimes be lower than contemporary, post-dam flows and much lower than pre-dam flows under this policy. Further, the low reservoir levels associated with this policy (Figure 9.27) may limit the ability to implement designer flow releases from Flaming Gorge.

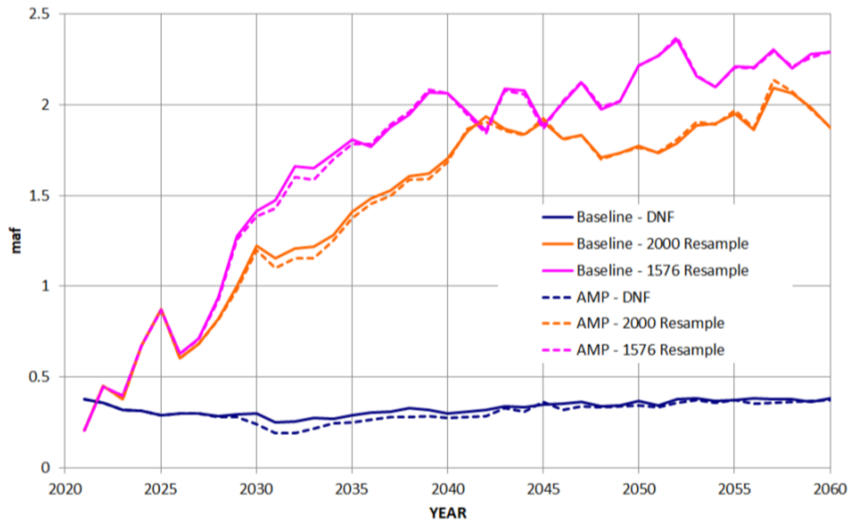

Figure 9.28. Average shortage volumes to the Lower Basin and Mexico with the Flaming Gorge to Powell Backup AMP, considering the DNF, Millennium Drought (*2000 Resample*), and Paleo Tree Ring Drought (*1576 Resample*) hydrologic conditions.

10. Conclusions

The primary purpose of this White Paper is to provide provocative new ideas. Some of the alternative management paradigms presented here may be considered to be radical changes to the existing norms that have been institutionalized through the *Law of the River*. **We argue, however, and provide warning, that the current management approach that allows only incremental changes to the *Law of the River* may be insufficient to adapt to the future conditions of the basin.** Other approaches must be developed that consider the sustainability of water supplies alongside the integrity of other river resources including ecosystem conditions. The alternative management paradigms assessed in this study have been considered promising new approaches, but until now had not yet been sufficiently studied. We examine these potential alternatives under different assumptions of demands, inflows, and operating rules to assess their implications and potential challenges.

Ten important conclusions arise from this work are presented below:

1. **The Colorado River has been profoundly altered from its highest reaches to its delta**

   The construction of large Lower Basin diversions, transbasin diversions high in the Upper Basin, and large dams throughout the basin have profoundly altered the native river ecosystem. The flow regime in the Upper Basin has changed the least compared to the rest of the basin, however, significant consumptive uses, including large headwater transbasin diversions, have significantly reduced the flows in this region and diminished the volume of water that reaches Lake Powell. In the Grand Canyon, the flow regime and aspects of water quality were radically transformed following the closure of Glen Canyon Dam in 1963. The lower river downstream from Lake Mead has been substantially altered by reservoir releases that are completely outside of a natural flow regime, and the river is progressively dewatered and canalized as it flows downstream. The most significant changes have been in the Delta where the river no longer flows into the ocean. Following nearly two decades of what has been termed the 'Millennium Drought,' the combined storage of Lake Powell and Lake Mead has fallen to 40% capacity; there is no indication that future hydrologic or environmental conditions will improve without drastic management changes. This history and the current depleted condition of the river system suggests that the forthcoming negotiations over future management must seriously consider how to protect or even improve the wider benefits that the river resources provide to society.

2. Unrealistic future depletion projections for the Upper Basin confound planning

The UCRC projections of future growth in Upper Basin depletions are unlikely to be realized, and they are, perhaps, implausible. Sustainable management of the Colorado River will primarily be achieved by balancing consumptive uses of the river with the available supply, and overestimation of future Upper Basin uses distorts perspectives of future supply-demand imbalances. In 2016, the UCRC projected that consumptive uses in 2020 would be 894,000 af/year more than the average annual consumptive uses between 1988 and 2018. The UCRC projections also assume that Upper Basin consumptive uses further increase by an additional 675,000 af/year by 2060. In percentage terms, these UCRC projections for 2020 are already 23% higher than actual use and would be more than 40% higher than present use in 2060 (i.e., 1.57 maf/year greater than 1988-2018 values). We demonstrate that Upper Basin consumptive uses have been nearly flat since 1988, and there are no planned or even conceptual projects that could possibly increase Upper Basin demands to the extent projected by the UCRC.

To properly plan for the future, sound projections of future depletions are required. Unreasonable and unjustified estimations create the impression that compact delivery violations, very low Powell and Mead storage content, and greater Lower Basin shortages, are inevitable. Such distortions mislead the public about the magnitude of the impending water supply crisis and make identifying solutions to an already difficult problem even harder.

3. Climate change is causing flow declines and additional declines are likely to occur

Climate change is impacting the river, and flows during 2000-2018 are approximately 18% less than the 20th century average (1906-1999). Reclamation and water users across the basin must recognize that the hydrologic conditions which have occurred since 2000 might be a 'new normal.' However, simply reframing a new baseline may not be sufficient. Additional declines are likely to occur as rising temperatures increase aridity, resulting in less runoff from the watershed for a given amount of precipitation. The on-going Millennium Drought may not be a drought at all, but instead may represent the 'new abnormal' to which the basin must adjust. The hydrologic conditions since 2000 are similar to the RCP4.5_065 scenario which shows at 2020 a 16% decline from 20th century conditions (12.8 maf/year), and then declining by an additional 5% by 2050 to 12 maf/year. 'Abnormal' in this case means ever-changing conditions, a moving target that presents new and difficult water management challenges unlike any previously encountered. Water managers and responsible stakeholders must plan for a range of possible futures with respect to Colorado River water supplies, including significant flow declines even beyond the RCP4.5_065 scenario.

4. **The Colorado River exists in a tenuous balance between supplies, demands and storage. Unplanned changes in this balance are likely to lead to highly undesirable outcomes.**

Since the onset of the Millennium Drought in 2000, it has become clear that the Colorado River system is in a tenuous mass balance where demands are met by a combination of historically low inflows, limited conservation commitments by existing users in the Lower Basin and Mexico, and diminishing water in storage. Any further perturbation that reduces inflows, increases demands, or lessens conservation efforts will drive the system to imbalance with a series of cascading and highly undesirable outcomes including Upper Basin Compact violations, draining Powell and Mead, and large Lower Basin water shortages.

For example, the Millennium Drought (2000-2018) and Upper Basin consumptive use during this period (3.89 maf/year of depletions excluding Upper Basin CRSP evaporation) resulted in average annual inflows into Lake Powell of only 8.45 maf/year. After annual average evaporation losses from Lake Powell (~0.6 maf including 'salvage' evaporation) and Lake Mead (~0.7 maf), the current operational rules allowed the reservoirs to continue supplying the needs of the Lower Basin States (7.5 maf), and Mexico (1.5 maf), while downstream evaporation losses (~0.3 maf) also occurred. However, **the current operational scheme resulted in the depletion of 26 maf of storage in Lakes Powell and Mead during the 19-year period from 2000-2018. Today, the remaining combined Powell – Mead storage is only 20.3 maf; therefore, a risk in meeting future water-supply needs clearly exists.** Our modeling shows that if the current hydrologic condition of the Millenium Drought persists and no further actions are taken, the combined storage would fall to 15 maf during the next 20 years, and average annual shortages to the Lower Basin of 1 maf/year would be expected in the absence of Upper Basin curtailments resulting from a compact call.

If the Millennium Drought conditions continue and the 2007 UCRC future depletion projections materialize, the Colorado River's water supply cannot be sustainably managed. These depletions would cause the inflows into Powell to drop below even the lowest interpretation of Upper Basin Compact obligations (75 maf during 10 years) by 2035. By 2045, Lake Powell and Lake Mead would drop to near dead storage (5 maf combined storage) and by 2040 Lower Basin shortages are predicted to average almost 2 maf/year in the absence of Upper Basin curtailments. If a compact call were declared based on crossing a threshold of 82.5 maf during 10 years, this could occur as early as 2026 and would be likely by 2030.

As expected with this tenuous mass balance, further decreases in inflows would also lead to undesirable outcomes, even if the Upper Basin demands do not increase. The magnitude and speed at which undesirable outcomes occur is roughly proportional to the combined increase in demands and reductions in inflows.

5. **Likely lower inflows and/or any increases to Upper Basin consumptive uses will result in a difficult Basinwide reckoning**

   Because of the effects of climate change, future flows in the river will likely continue to decline beyond the current ~18% reduction relative to the 20th century (1906-1999). Under this scenario, the basin will soon face a tipping point with frequent and possibly large compact delivery violations and untenable Powell and Mead storage volumes. With less water available in the upstream reaches, many Upper Basin diversions will be reduced due to a physical lack of water. Furthermore, the Upper Basin will have to choose among curtailing existing uses to meet compact obligations, legally challenging the 1922 Compact, or seeking a settlement with the Lower Basin that equitably distributes the risk of climate change. The Lower Basin will have to choose either hoping the Upper Basin will continue to deliver a minimum of 8.25 maf/year at Lee Ferry, litigation to force the matter, or reaching an equitable settlement on climate change. If the Upper Basin were to somehow increase its demands, this would create an even greater sustainability challenge in the face of declining flows.

The following three findings are based on modeling analyses of different Alternative Management Paradigms.

6. **Lower Basin shortage triggers based on combined Powell and Mead Storage are more logical and clearer than existing triggers**

   There are significant advantages of using the combined storage of Lake Powell and Lake Mead as the principal determinant of Lower Basin shortages. Such a metric would encourage a more accurate perspective on the state and security of Colorado River's water supply and would discourage the currently fragmented view in which Lake Powell and Lake Mead are considered two separate reservoirs. Not only does this method provide a clearer and more logical way to declare shortages in the Lower Basin, but it also allows operational flexibility to benefit environmental conditions along the river in the Grand Canyon.

7. **Neither Fill Mead First nor Fill Powell First promote or improve Lower Basin water security**

Neither a Fill Mead First nor a Fill Powell First management strategy would significantly address the basin-scale water supply sustainability or security for downstream users. The savings in evaporation losses from preferentially storing water in one reservoir does not significantly alter the risks that the basin faces from over-allocation, drought, and climate change. If either of these strategies were to be pursued as characterized in this study, large shifts between flow regimes and swings in water temperatures in the Grand Canyon would occur based on maximum or minimum elevation thresholds. CRSS and a reservoir temperature release model can be used to identify the advantages and potential fatal flaws of these two alternatives, and explore any potential future variations of them.

8. **Flaming Gorge Releases provide little Upper and Lower Basin Risk Protection**

   Emergency releases from Flaming Gorge when Lake Powell is low provide only minimal benefits under the current operational rules. On average, this alternative management paradigm adds around 1 maf of water to Lake Powell in infrequent transfers. Unfortunately, after equalization and balancing releases occur, compact violations and shortages to Lower Basin water users decrease only slightly. In mass balance terms, the size of this release is quite small and thus has little effect on the overall system state. One benefit, however, would be more natural flow regimes of the Green River during these critical times.

The last two findings are logical outcomes from all the above.

9. **Humans have significant control over demands but little control over inflows**

   Imbalances in supply and demand can only be solved by increasing supply or decreasing demand. Unlike future climate-influenced inflows where humans have little or no control, humans can exercise complete control over demands. Adding new demands to an uncertain, and increasingly stressed, system widens the imbalance and exacerbates the already difficult but important challenge of finding ways for existing users to reduce demands. New demands in the era of climate change resulting in decreasing flows are the equivalent of self-inflicted wounds. Equitable demand reductions will be an important part of water management in the Colorado River Basin in the era of climate change.

10. **Dire situations require solutions far from historic norms**

    An increasingly limited and uncertain water supply should force water managers to confront an uncomfortable reality: the Colorado River system is overallocated and even existing allocations can no longer be guaranteed. At the same time, the river is now controlled by massive infrastructure, and more than one hundred years of complex laws, court decrees, treaties, and compacts govern its operation. Although our institutions and infrastructure have served us well, staying within their confines may inhibit the necessary solutions. American society is on the path of a collision between nature and the structures and institutions of humankind. In the 20th century on the Colorado River, nature was bent to human will. Because we are now fully consuming its waters, and inflows are expected to decline—in the 21st century humans will be forced to bend to the will of nature. Resolution of these problems that consider equity, the economy and the environment will require previously unthinkable solutions that challenge the limitations of our existing institutions and infrastructure. Such solutions are possible but will require a willingness to put aside old ideas and act boldly.

Appendices

Appendix 1. Other Water Supply Metrics

This appendix summarizes potential water supply metrics that might be used to represent interests from stakeholders, water managers, river scientists and others that are interested in the basin. In Section 8 we presented a number of metrics to evaluate the implications of alternative management paradigms on water supply and ecosystems, and in Section 9 we demonstrated the performance of these metrics under particular alternative management paradigms. In this section, we introduce additional water supply metrics that are discussed in the scientific literature, which might be helpful for future planning and management of the Colorado River.

There are other metrics that are of interest to particular stakeholders, such as the Partnership Tribes. Reclamation has been in an ongoing process to modify the structure of CRSS parse demands, which are associated with tribal ownership, from previously lumped demands that include both tribal and non-tribal water. As of the April 2020 version of CRSS, the reliability of water supply to many tribal water uses can be coarsely evaluated by reporting the shortages to the elements that have been parsed (USBR, 2018). However, CRSS does not represent the physical or temporal detail of individual water rights, therefore additional tools such as StateMod (Colorado Water Conservation Board, 2019) might be helpful in accurately determining tribe water shortages.

Reservoir levels that are associated with the physical ability of tribal water to be utilized provides another important type of metric. For example, reporting the likelihood of maintaining the Navajo Reservoir pool elevation above 5,990 ft msl is valuable because this is the minimum water level where the Navajo Indian Irrigation Project Diversion facilities are operable (USBR, 2012).

In addition to showing averages or percent exceedances of time series results from CRSS, there are other statistical summaries of results that can be used to indicate policy performance. These metrics include:

- ***Reliability***: The reliability of a water supply can be defined as the number of instances that the available supply is considered satisfactory, divided by the total number instances considered on a time series. For example, if we are considering a 40 year planning horizon and we define a satisfactory state to be a delivery to the Lower Basin and Mexico water users of at least a 9 maf/yr, but the system is is only able to achieve this objective in 35 years through this horizon, then the reliability is 87.5% (= 35 years / 40 years). This metric measures how likely the system is not to fail and higher reliability value is clearly preferred.
- ***Resilience***: Resilience is defined as the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a potentially hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions (Lavell et al., 2012). From a system recovery perspective, resilience is described mathematically as

the probability of having a satisfactory value in time period t+1, given an unsatisfactory value in any time period t. Using the same example mentioned above, if there are five years of insufficient water delivery to the Lower Basin and Mexico, but only four of those years are followed by satisfactory instances, then the resilience is 80% (= 4 years / 5 years). This metric measures the likelihood of system recovery from an unsatisfactory state.

- ***Vulnerability***: Vulnerability is defined as the propensity or predisposition to be adversely affected in general (Lavell et al., 2012). In the Basin Study (USBR, 2012), a system is considered in a vulnerable state when a vulnerability threshold is exceeded. There are multiple mathematical ways to define vulnerability, such as (1) the proportion of all years when a vulnerability threshold was exceeded; (2) the portion of all simulation traces when a vulnerability threshold was exceeded at least one time during the planning horizon; (3) maximum or average exceedance to a vulnerability threshold. These metrics help evaluate the severeness of system failure.
- ***Robustness***: Robustness of a strategy or a plan measures the ability to perform well across a wide range of uncertain future conditions (Lavell et al., 2012), and the mathematical definitions vary in each case. There are two major ways to measure robustness. One is regret robustness, which measures the deviation of a policy's performance from a benchmark system performance. The other is satisfying robustness, which is more common and measures the ability to meet multiple performance requirements across a wide range of uncertain futures (Alexander, 2018). Robustness analyses are often used to identify policies that are acceptable under the widest variety of circumstances or alternatively can be perceived as the metric showing the overall system performance.

In addition to the quantitative metrics introduced above, there are other important qualitative metrics such as adaptability. This metric has no explicit mathematical definition, but it provides a concept of adapting to future changes. The key idea of this concept is that a policy that achieves high reliability, resilience, and robustness today may not be reliable, resilient, or robust in the future, especially when severe conditions such as extreme drought occur, when more information become available, or more measurements and better understanding of hydrology and demand become available. Therefore, adaptability requires operating policies to be ready to change once those changes occur.

Appendix 2. How does Lake Powell water storage influence release temperatures and Grand Canyon fishes?

Introduction

Current Lake Powell reservoir operations for equalization and the Upper Basin drought contingency plan are articulated as target reservoir surface elevations and storage volumes. This analysis asks and answers the question: How does water storage in Lake Powell influence release temperatures and Grand Canyon fishes?

Prior Work

Reservoir release temperature is a key driver of fish community composition in Grand Canyon (Dibble et al., 2020) due to differences in temperature requirements across species (Figure A1). During summer months, reservoir release water warms as it travels downstream to Lake Mead. Prior efforts have used process-based and empirically based models to relate reservoir water surface elevations to release temperature and release temperature to downstream temperatures (Dibble et al., 2020; Mihalevich et al., 2020; USBR, 2007, Appendix F; Wright et al., 2009). These models require the user to specify difficult-to-predict inputs such as incoming solar radiation and air temperature.

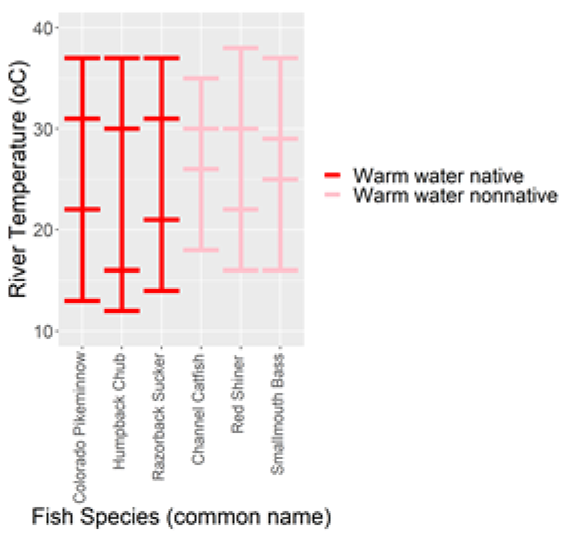

Figure A1. Minimum, minimum optimal, maximum optimal, and maximum temperature suitability (horizontal bars) for select native (red) and nonnative (pink) warm-water fish species of the Grand Canyon. Data from Dibble et al. (2020).

As an alternative, we use, link, and characterize uncertainties in the primary reservoir water level (USBR, 2020b), release temperature (GCMRC, 2020), and depth-temperature profile

(Vernieu, 2015) data. We then define ecologically-relevant release temperature scenarios that span different outcomes for native and non-native fish of the Grand Canyon. We visualize the reservoir elevation zones that correspond to each release temperature scenario.

Methods

First, we use date and time information to link the primary observed reservoir water level (USBR, 2020b), release temperature (GCMRC, 2020), and depth-temperature profile (Vernieu, 2015) data sets.

Second, we define ecologically-relevant release temperature scenarios with different impacts on native and non-native fishes in the Grand Canyon (Table A1). The scenarios for <12^{o}C and <15^{o}C reflect that native, warm-water fish have slightly lower minimum and minimum optimal temperature thresholds than non-native fish (Figure A1).

Scenario (^{o}C)	Ecological Meaning	Years Observed
< 12	Year-round release temperatures where native fish persisted, but likely rely on warmer tributaries for reproduction and growth.	Consistently before 2003
< 15	These summer temperatures correspond with increased relative abundance of native fish downstream. Other factors, such barriers to non-native species, may contribute to these trends as well.	More frequently after 2003
< 18	Uncertain outcome. May benefit native fish, but may also harm them by facilitating invasion by warm water non-natives.	Not since 1973
> 18	Outcome highly uncertain for native fish. Tailwater trout fishery unlikely to persist.	Not since 1973

Table A1. Reservoir release temperature scenarios

Third, we plot the daily range of observed release temperature data (GCMRC, 2020) for different water surface elevations (Figure A2, blue).

Fourth, we translate the depth-temperature profile data (Vernieu, 2015) at the Wahweap station to show anticipated release temperatures at water surface elevations *below* historically observed elevations (Figure A2, red). The translation assumes that solar radiation is the primary driver of temperature in the reservoir epilimnion and that water temperatures at shallow depths below the water surface will be similar regardless if water surface elevation is 3490, 3500, 3600, 3610, etc. ft msl.

- For example, we translate a temperature profile measurement of 18°C 10 feet below (depth = 10 feet) an observed water surface elevation of 3,610 ft msl down to a water surface elevation of 3,500 ft msl. 10 feet below the new water surface elevation of 3,500 ft msl will give a release temperature of 18°C at the turbine release elevation of 3,490 ft msl.
- Additionally, we decrease the turbine release temperature by 0.5, 1, or 2°C for Wahweap profile temperatures greater than 11, 13, and 15 °C. This adjustment adjusts for differences between Wahweap and release temperatures due to turbine entrainment and other factors (Figure A3).

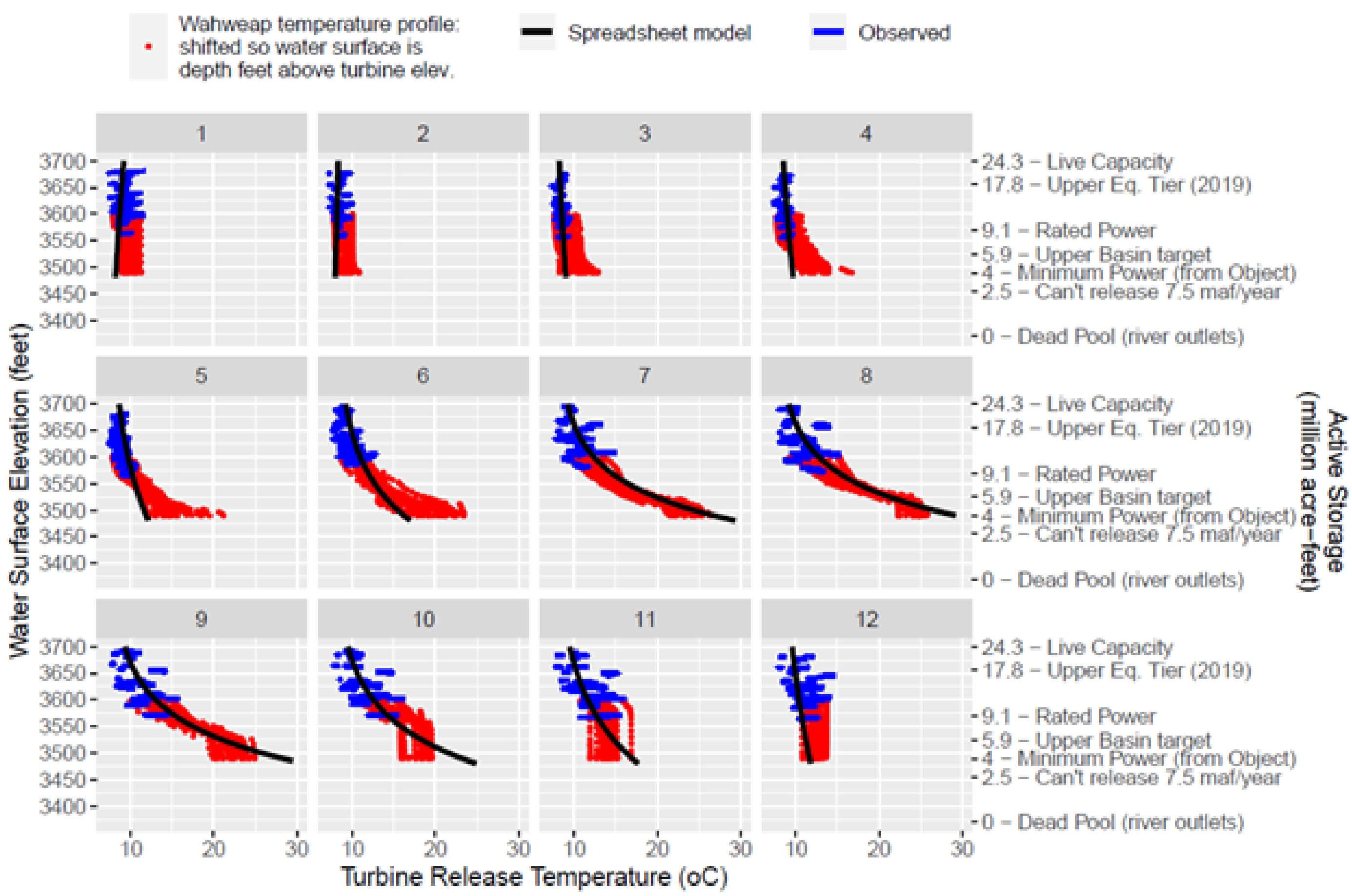

Figure A2. Compare observed penstock release temperature (blue) and translated depth-temperature profile data (red). Black lines show estimated release by an empirical spreadsheet model (Dibble et al., 2020).

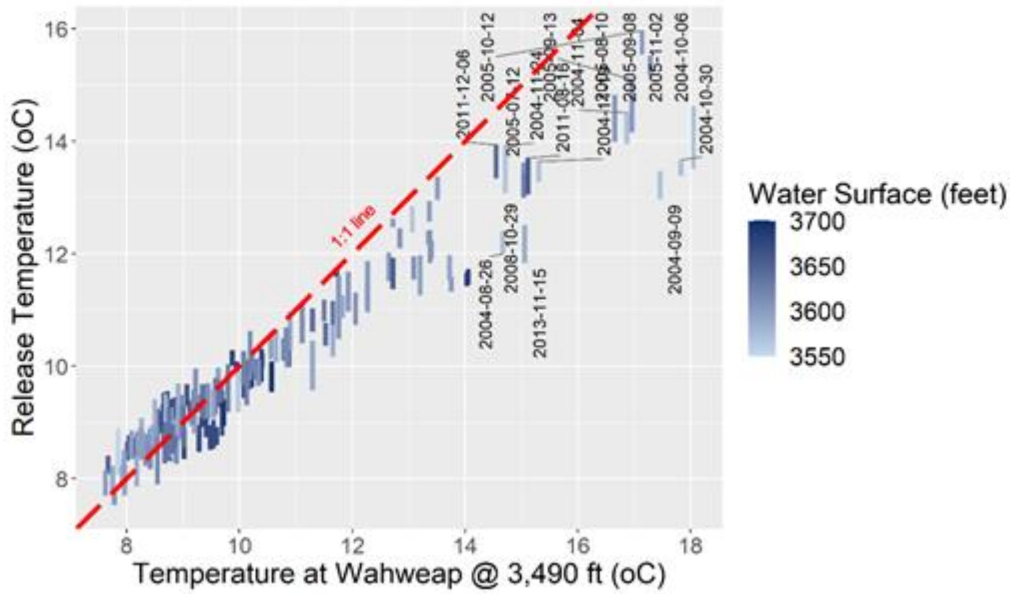

Figure A3. Comparison of turbine release and Wahweap profile temperatures at the turbine elevation of 3,490 ft msl.

Fifth, we identify the range of reservoir water surface elevations for each release temperature scenario. For example, in August, we might see a 15^{o}C release through the turbine for reservoir elevations between 3,525 and 3,610 ft msl.

Finally, we stack into bars the reservoir elevation ranges for each release temperature scenario (Figure A4).

Results

Examination of the stacked bars in Figure A4 shows:

- Water levels above 3,675 ft msl will cool releases below 12^{o}C (dark blue bars). Native fish may persist with these year-round release temperatures but likely rely on warmer tributaries for reproduction and growth.
- Elevation ranges of 3,600 to 3675 ft msl in August, September, and October will keep release temperatures below 15^{o}C (light blue bars). These release temperatures may see increased relative abundance of native fish downstream, but other factors, such as predation by nonnatives, may contribute.
- August to October water levels below 3,600 ft msl will warm releases (<18^{o}C) so that outcomes are uncertain for native fish (pink bars). Native fish may face invasion and predation by non-native warmwater fish.
- Water levels below 3,525 ft msl will further warm releases above 18^{o}C (red bars). Impacts for native fish are very uncertain. The tailwater trout fishery may also perish.

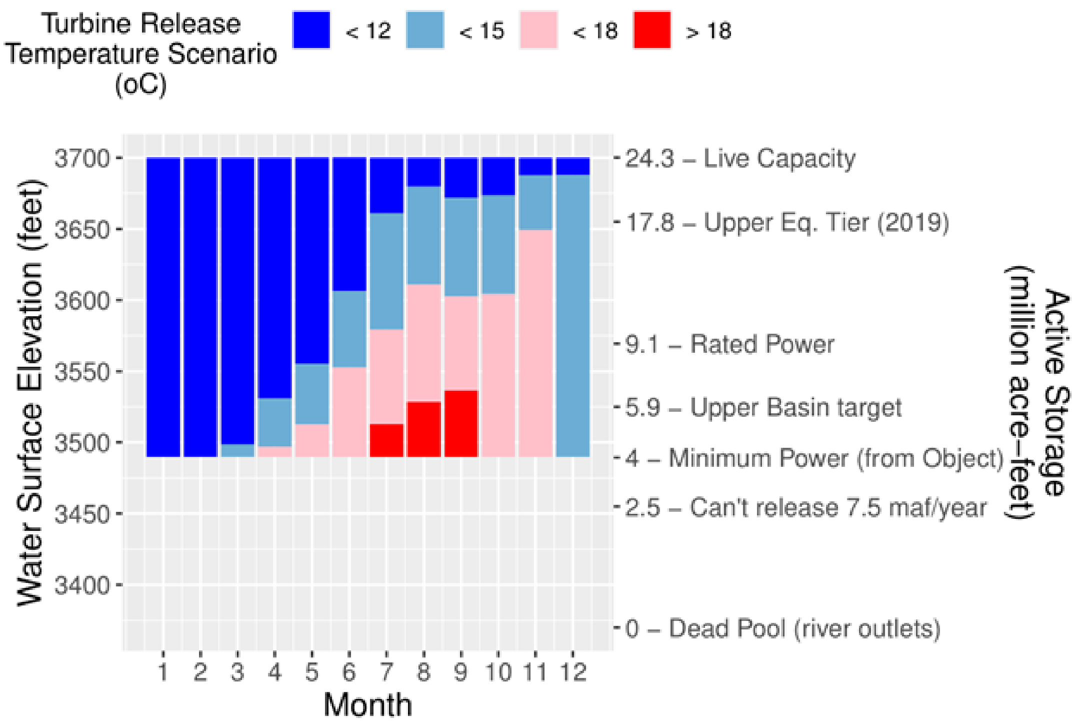

Figure A4. Lake Powell water surface elevations to maintain release temperature scenarios through the turbines. Elevation ranges consider uncertainty in observed and water profile data.

If Glen Canyon Dam managers forgo penstock releases and release water through the river outlets, the same release temperatures can be achieved with reservoir water surface elevations that are 100 to 125 feet lower (Figure A5). For example, 15ºC releases can be maintained through September, October, and November with reservoir elevations down to 3,500 ft msl (compared to 3,600 ft msl if releasing all water through the penstocks). If managers release water through both the penstocks and river outlets, managers can maintain release temperatures at water surface levels below levels shown in Figure A4 and above levels shown in Figure A5.

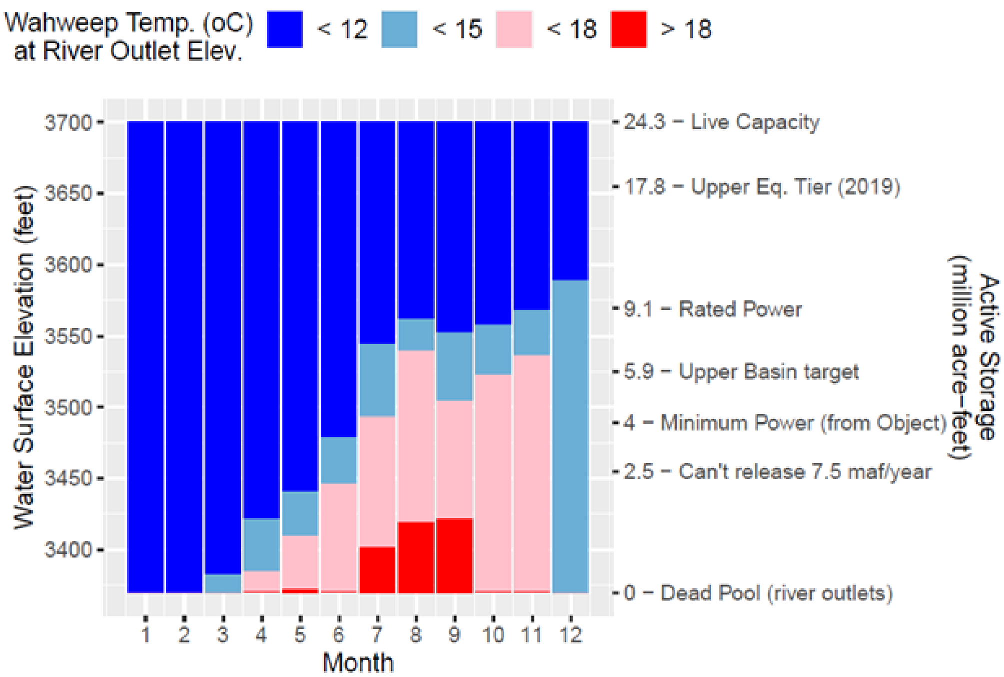

Figure A5. Lake Powell water surface elevations to maintain temperature scenarios through the river outlets. Elevation ranges consider uncertainty in observed and water profile data.

The reservoir water surface elevations in Figures 4 or 5 can help modify the Fill Mead First and Fill Powell First alternative management paradigms (AMPs) to benefit native fish of the Grand Canyon. For example, set the Powell-Low and Powell High parameters to 3,600 and 3,675 ft msl (range for light blue bars) so that Powell release temperatures are more frequently less than 15°C. The analysis also shows potential to define summer or monthly reservoir targets and better align operations with key periods important to native fish when reservoir releases are warmest.

Limitations of this analysis include the following assumptions:

1. Future relationships between reservoir release temperatures and reservoir water surface elevations will resemble the historical data.
2. The future relationship between reservoir release temperature and temperature at Wahweap at the turbine elevation will resemble the historical data.
3. This analysis ignores flow dynamics, entrainment, and mixing of different temperature water from elevations near the intakes of the penstocks and river outlets.
4. The future timing and magnitude of annual reservoir turnover will resemble historical turnover.

Data, Model, and Code Availability
The data, models, and code that support this analysis are available at Rosenberg (2020).

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